Design and Development of the EcoCAR Vehicle and the Vehicle Controls Providing Efficiency and Drivability

THESIS

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Abstract

The OSU EcoCAR Team is comprised of a diverse group of students ranging from underclassmen to graduate and engineering to business. This diverse team provides both the ability to take on aggressive designs and meet ambitious goals, but also presents a unique set of management and leadership responsibilities. The team management and growth was critical to being successful in meeting timelines and goals amongst diverse experience and levels of involvement. First, this thesis will include elements and details on how this team management and leadership was structured and changed to produce results. Next, the EcoCAR competition vehicle was designed to maximize efficiency and performance while minimizing emissions and petroleum usage. The Ohio State team designed a unique extended-range electric vehicle (E-REV), which uses two electric machines and a battery to power the vehicle for 40-45 miles until an E85 engine turns on and provides the power. The OSU vehicle is unique in its capability to use the front powertrain as an electric drive, auxiliary power unit (APU), or hybrid drive. The design will be explained in this thesis with a specific focus on the benefits of the design and the unique transmission system designed to provide vehicle function. The vehicle design presents a wide variety of controls options and challenges when managing energy, drivability, and performance. This thesis will also dive deeply into controls algorithms and decisions for the vehicle control algorithm design, calibration, and improvements. Topics such as controls hardware and software structure will be explained along with a
variety of test results from simulation and vehicle testing. The results show a very comprehensive control system and vehicle design capable of a wide variety of operating conditions and speeds. In all cases, the design provides robust and reliable operation with high efficiency and performance.
Dedication

This document is dedicated to my beautiful wife Katie for all her patience, support, and love during completion of graduate school and the EcoCAR Competition.
Acknowledgments

I would like to thank the EcoCAR Team for the enormous amount of help I received from my teammates on completing the EcoCAR vehicle. I would also like to thank Dr. Shawn Midlam-Mohler for his tremendous dedication to the team as an advisor and mentor his passion for education, engineering, and innovation is inspiring and contagious. I would also like to thank Dr. Midlam-Mohler for his lively conversations about vehicle design and controls. I would also like to thank Bernhard (Bernie) Grimm for his outstanding help with the control of the EcoCAR vehicle’s electronic throttle and his work with the all electric mode software. Additionally, I would like to thank Dr. Giorgio Rizzoni for his tremendous support of projects such as EcoCAR and the students that are involved with them. Lastly, I would like to thank friends, co-workers, and teammates Brad Cooley, Beth Bezaire, and John Kruckenber as well as many other EcoCAR teammates for their help and advice in many aspects of research and development of my thesis, course work, and overall EcoCAR Team Leadership.
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Publications

“Addressing Drivability in an Extended Range Electric Vehicle Running an Equivalent Consumption Minimization Strategy (ECMS)”

Fields of Study

Major Field: Electrical and Computer Engineering
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CHAPTER 1

INTRODUCTION

1.1 Motivation

Today’s vehicles are subject to increasingly stringent fuel economy and emissions standards in addition to consumer expectations rising for drivability, performance, and decreased noise. Development of vehicles capable of meeting or exceeding regulation standards, while still attracting consumers requires many advanced technologies and many well trained engineers. Leading a program like EcoCAR where engineering students can gain exposure and experience during undergraduate and graduate studies is important to ensuring the transportation industry does not fall behind in training new engineers and gaining access to new ideas, talent, and technology. Developing and researching alternative vehicles and powertrains such as that designed by the OSU EcoCAR team is extremely important to promoting innovation and creativity in how industry will provide a sustainable transportation future. This thesis will address both leadership and management of the OSU EcoCAR team as well as the design and controls of the EcoCAR vehicle.
1.2 EcoCAR: The Next Challenge

The Ohio State University (OSU) is one of sixteen North American universities that participated in EcoCAR: The Next Challenge (EcoCAR), a vehicle development competition sponsored by the United States Department of Energy (DOE), General Motors (GM), Natural Resources Canada, and many others. This three-year competition challenged student teams to re-engineer a crossover-utility vehicle for improved fuel economy and emissions while maintaining vehicle performance and consumer acceptability. Each team’s task was to design, build, and refine a fully-functioning, prototype vehicle. To accomplish this goal, teams followed a vehicle development process modeled after the practice used by General Motors Corporation. At the end of each year, teams participated in a several day competition event in which progress and vehicles were evaluated over a number of static and dynamic tests.

1.2.1 Vehicle Development Process

The EcoCAR Vehicle Development Process has multiple elements and definitions. First, the timeline structure can be seen in Figure 1 where it shows a three year process with three categories of electrical, mechanical, and controls. Figure 1 shows that the modeling, vehicle goals, and predictions are set in the first year and summarized in the end by the project initiation benchmark. Next, Figure 1 shows that vehicle construction begins in the second year ended by a vehicle design review of the mule prototype. In addition, the mule vehicle is evaluated by dynamic testing and review of the operation and function of the constructed system. Lastly, the third and final year of the
development process focuses on refinement and optimization, which is ended by a vehicle testing complete gateway ending the EcoCAR development process.

Figure 1: EcoCAR Vehicle Development Process Swim Lanes

In addition to, the overall vehicle development process, many of the categories follow a process like that outlined in Figure 2 for the controls development. This process outlines the expected flow of controls development with the expectation that a portion of the process will include revising and revisiting previous steps as testing reveals improvements or a need for improvements.
1.3 Thesis Overview

This thesis discusses development of the Ohio State University’s vehicle architecture for the EcoCAR competition with an in-depth analysis and modeling of the vehicle energy consumption and control system. An overview of the chapters contained in this thesis is provided below.

- Chapter 2 – Literature Review
  - Chapter 2 summarizes three topics.
    1. Various hybrid architectures investigated
    2. Supervisory and energy minimization strategies
3. Drivability metrics and improvement to controls for drivability purposes.

- Chapter 3 – EcoCAR Team Development, Management, and Structure
  - Chapter 3 discusses the work done to grow a multi-disciplinary team and manage detailed design groups and projects throughout the three year design and development process.

- Chapter 4 – Vehicle Architecture Detailed Design Overview
  - Chapter 4 details the OSU EcoCAR vehicle design including the unique dual clutch transmission system and various supporting aspects such as: battery, high voltage systems, and engine controls.

- Chapter 5 – Supervisory Control System (Experimental)
  - Chapter 5 explains decisions for various aspects of the vehicle control and details operation and optimization. In addition results comparing initial controls operation to final calibrated controls operation are compared.

- Chapter 6 – Vehicle Drivability Controls Improvements (Experimental)
  - Chapter 6 details the controls additions, modifications, or considerations for drivability and presents the results from those changes.

- Chapter 7 – Conclusions and Future Work
  - Chapter 7 summarizes the work completed and future applications or additions.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction
The Ohio State University’s extended-range electric vehicle developed for the EcoCAR competition is an extended-range electric vehicle employing a custom dual clutch system allowing limited series and parallel hybrid operation. Therefore, the first focus of this literature review is an investigation of traditional hybrid electric vehicle architectures. The second focus is on supervisory controls, specifically those that minimize energy use. Lastly, there is a review of vehicle drivability as well as methods for improving it.

2.2 Hybrid Vehicle Architectures
A hybrid vehicle is defined as a vehicle using a combination of two energy sources in order to propel the vehicle. The investigation of hybrid vehicle architectures stretches through various types of systems, the first being a charge sustaining hybrid and the second being a charge depleting hybrid. A charge sustaining hybrid is one that does not use external electric power to charge the battery system, and instead the battery is used as a buffer to allow higher efficiency operation of the system. In this way, a charge sustaining hybrid is restricted to having the engine involved in operation nearly all the time where as a charge depleting hybrid has greater freedom in operating the engine.
Additionally, charge sustaining hybrids typically have smaller batteries designed for brief power output or input needed to accelerate the vehicle or store electric energy captured from braking for later use. A charge depleting hybrid can operate in a variety of ways, but most importantly uses energy from charging up the vehicle battery from an external connection. A charge depleting hybrid then operates with decreased fuel consumption by using electrical energy from a larger battery pack, which is eventually depleted. When a charge depleting hybrid reaches a certain battery charge it must begin charge sustaining operation, but has access to a larger capacity battery. Charge sustaining and charge depleting systems can use a wide variety of architectures with the primary difference being battery size and use. Architectures such as parallel, series, and multi-mode are all investigated. Figure 3 shows a conceptual illustration of hybrids where the first energy source is unidirectional and the second in bidirectional.
2.2.1 Parallel Architectures

Among hybrid architectures there are many configurations, but one distinct category is a parallel configuration. In this type of architecture the engine and electric propulsion system have a mechanical link to the vehicle’s wheels. The high level conceptual view of this system can be seen in Figure 4 where it is shown that the engine and electric machine can provide tractive torque. This architecture has the primary advantage that by sharing the propulsion between devices and optimization can be done for balancing a shared load. More importantly, downsizing of components can be done without sacrificing performance, since no one source has to provide all the tractive torque. Energy efficiency is primarily due to downsizing, load shifting, and lower energy loss as compared to the
extra conversion losses associated with generating power for an electric drive system. The use of load shifting in parallel hybrid architectures helps to improve overall engine efficiency. Load shifting is when the electric machine and gearbox specifically change the engine operating point to a higher efficiency point by either loading the engine by generating power for later use or relieving engine load by supplementing output torque.

Figure 4: Conceptual Illustration of a Parallel Hybrid Drivetrain [2]

The first disadvantage of parallel powertrains is mechanical couplings and controls are more complicated [2]. A second disadvantage is the mechanical coupling dictates the engine operating point rather than controls being able to distinctly choose a narrow high efficiency operating point or region [2].
2.2.2 Series Architectures

Another distinct hybrid architecture category is a series configuration. In this type of architecture there is an engine and generator whose sole purpose is to provide electricity to the battery and tractive system. In this series architecture, an electric propulsion system provides all the tractive torque with its input supplemented by the battery. Figure 5 shows a high level view of this basic conceptual architecture.

![Diagram of a Series Hybrid Drivetrain](image)

**Figure 5: Conceptual Illustration of a Series Hybrid Drivetrain [2]**

This architecture offers the primary advantage of a very simple control, design, and integration. This architecture also offers a very significant downsizing since the engine only generates average power and never peak power. There are three distinct disadvantages in series architectures, with the first being the tractive power comes only from one of the three possible propulsion sources, which requires it to be capable of
meeting the entire performance need. Secondly, there are twice the energy form conversions required (mechanical from engine to electric through generator and then to mechanical again through the traction motor); therefore on the highway energy losses from these conversions begin to outweigh the gains given from operating in an optimal point. The third disadvantage of series architectures is difficult to measure, but is the added cost of a generator and power electronics as compared to a parallel system, which uses only the tractive system in conjunction with the engine. [2]

2.2.3 Multi-Mode Architectures

The two basic categories of hybrids with series and parallel are often mixed in a multi-mode design that makes operation in both modes possible. The multi-mode operation is typically encompassed in a transmission, which uses clutches and planetary gear sets to provide operation in both series and parallel within the system. The GM 2-mode transmission is a multi-mode system allowing series and parallel operation in addition to conventional fixed gear operation. Figure 6 shows the schematic cross section of the 2-mode system. This system offers two EVT modes, which can operate in a type of series function. Additionally, the system contains fixed gears, which allow parallel operation as well. The complexities of this transmission also allow varying efficiencies by changing gear ratios, modes, and couplings. The system allowing series and parallel operation provides much of the advantages of both hybrid categories with few disadvantages. For example employing the EVT series type of operation the high efficiency engine operation can be achieved. Another example is with the parallel operation performance and towing can also be maintained or improved. Therefore, a multi-mode system provides the ideal
features from each hybrid category; however, it comes with extra cost, complexity, and controls in order to achieve gains and the final product.

Figure 6: Schematic Cross Section of the GM 2-mode System [3]

Many other designs and systems besides the GM 2-mode exist, such as, the Toyota synergy drive, which is simpler, but still offers series/parallel operation. Figure 7 shows a conceptual view of a Toyota type of drive system, which uses planetary gear sets to link the engine, generator, and traction drive. The parallel operation is offered by locking out the generator and using the planetary connections to mechanically bypass to the output. The other systems offer variations of ideal operation, which include single modes and no fixed gears, which are often ideal in slower stop and go operation. The primary disadvantages of any multi-mode architecture are complexity and spin losses. The cost of these systems is typically justified by the benefits, as shown by their market penetration, but also presents a disadvantage.
2.3 Supervisory Control Systems

Supervisory control systems have become increasingly important with hybrid architectures and additional electronic sub-systems, where the engine is no longer central to the overall operation. The supervisory control system dictates how various sub-systems contribute to the total vehicle operation and stability. A proper supervisory control system will maximize performance and energy efficiency while still providing a
smooth, robust, and stable operation of the system. The supervisory control can dictate actions such as power and torque, but also monitors driver commands, speed, and battery charge. In this way the supervisory control distributes power flow and torque splits based on meeting the driver’s request at that speed and vehicle status.

### 2.3.1 Rule-Based Control

Rule-based control is one of the simplest controls in concept, but tedious in implementation. The control system is operated by a set of calibrated rules and conditions, which dictate operation or operating regions. As conditions or commands change crossing thresholds are one type of rule, which trigger events or actions. Also rules may be simple true or false rather than providing a range and therefore, trigger an event or action based on true or false conditions. Rules, as described, are typically rigid and preset for the system to always follow and therefore, every condition must be calibrated and set.

Rule-based control typically enters into even the most elegant control system or algorithm and is often used to handle simple exceptions in the algorithm. An example of rule-based controls, which enter a broader algorithm, is a startup or shutdown sequence where no equation or system is easily designed to handle conditions and actions. Another use of rule-based control is to structure it over the algorithm to change modes and handle monitoring and reacting to faults or limits. In the same way, rule-based control also serves to command ON/OFF control such as the start/stop control of the engine in a hybrid or regulate boundaries of the battery SOC [8].
Rule-based control is avoided in the management of efficiency typically due to calibration effort where an algorithm solving an instantaneous optimization requires very little tuning to function well. Therefore, calibration effort is the primary reason to avoid a rule-based control and robust operation is typically the reason to choose a rule-based control for certain aspects of the system.

2.3.2 Equivalent Consumption Minimization Strategies (ECMS)

Minimizing the fuel consumption (or emissions) during a driving cycle is an optimal control problem in which the solution depends on the entire driving cycle. The solution of the global problem is difficult in simulation and impossible in real time, since at each instant the future part of the driving cycle is unknown. The Equivalent Consumption Minimization Strategy (ECMS) was introduced by Paganelli et al. [10] as a method to reduce this global problem to an instantaneous minimization problem, which is solved at each instant, without use of information regarding the future.

ECMS is based on the concept that, in charge-sustaining vehicles, the difference between the initial and final state of charge of the battery is very small, negligible with respect to the total energy used. This means that the electrical energy storage is used only as an energy buffer. Since all the energy ultimately comes from fuel, the battery can be seen as an auxiliary, reversible fuel tank; i.e. the electricity used during the battery discharge phase must be replenished at a later phase using the fuel from the engine (either directly or indirectly through a regenerative path), and vice-versa. In fact, a particular operating point of the powertrain leads to two cases:
• The battery power is positive (charge case): a recharge using the engine will produce some additional fuel consumption;
• The battery power is negative (discharge case): the stored electrical energy will be used to alleviate the engine load for running the car, which implies a fuel saving.

In both cases, the use of electrical energy can be associated to virtual (future) fuel consumption, which can be summed to the actual fuel consumption to obtain the equivalent fuel consumption:

\[ \dot{m}_{eqv} = \dot{m}_f + \dot{m}_{ress} = \dot{m}_f + s \frac{P_{ress}}{Q_{lhv}} \]  

(1)

Where \( \dot{m}_f \) is the fuel mass flow rate (instantaneous fuel consumption), \( Q_{lhv} \) is the lower heating value of the fuel (energy content per unit of mass), \( P_{ress} \) the electrical power exchange with the energy storage system, and \( \dot{m}_{ress} \) the virtual instantaneous fuel consumption corresponding to the use of electrical energy. \( s \) is called equivalency factor and is used to convert electrical power into fuel power; it plays an important role in the ECMS, as will be shown later. RESS (rechargeable energy storage system) is used instead of battery for more generality, since there are other electrical energy storage devices available (mainly electrochemical capacitors, or super capacitors).

The concept of equivalent fuel consumption is tied with the necessity of attributing a meaningful value to the equivalency parameter \( s \). This parameter is representative of future efficiency of the engine and the RESS, and its value affects both the charge sustainability and the effectiveness of the strategy: if it is too high, an excessive cost is attributed to the use of electrical energy and therefore the full hybridization potential is
not realized; if it is too low, the opposite happens and the RESS is depleted too soon (loss of charge sustainability).

In the case of a plug-in HEV, however, charge-depleting behavior is desirable and therefore the equivalence factor can be selected in such a way that it allows the discharge of the battery to the lower acceptable limit while minimizing the desired control objective.

It was shown [11] that very good results, comparable with the optimal solution of the global problem calculated off-line, are obtained by using two values of $s$, one for charging ($s_{ch}$) and the other for discharging ($s_{dis}$), each of them constant during a driving cycle. These values are different for different driving cycles and can be adapted during vehicle operation using adaptive ECMS algorithms [11], [12].

### 2.3.3 Neural Network Based Control

Neural network based controllers offer a unique approach to optimization of a hybrid control. An artificial neural network can be designed and implemented in a variety of ways with the primary goal of being capable of non-linear and adaptive control based on the system and conditions. A neural network requires a setup of the inputs and outputs, but most importantly the objective function or data by which it is trained or adapted. Neural networks provide many advantages and disadvantages such as those shown in Table 1.
Table 1: Advantages and Disadvantages of Neural Networks [14]

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Learning ability</td>
<td>• No knowledge representation</td>
</tr>
<tr>
<td>• Generalization and association ability</td>
<td>• No expert knowledge</td>
</tr>
<tr>
<td>• Uncertainty tolerance</td>
<td>• Convergence problems</td>
</tr>
<tr>
<td>• Fault tolerance</td>
<td>• Hardware and software requirements</td>
</tr>
<tr>
<td>• Various models and parametric approach</td>
<td>• Training prior to use</td>
</tr>
<tr>
<td>• Real-time operation</td>
<td></td>
</tr>
<tr>
<td>• Optimization ability</td>
<td></td>
</tr>
<tr>
<td>• Nonlinearity</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The neural network approach to hybrid control optimization presents a challenge primarily in convergence and computation requirements, but offers a variety of calibration or training methods. First, training can be done off-line with a large set of data, which would allow for an inverse network type to be created. Another method would be to create a high accuracy model of the system to generate the training data. Then the last method is to create an objective function for which the network will be trained to achieve, which would require recursive training to train the neural network. However, this intensive training of the system would not provide the desired adaptive element unless error was included as an input term. Therefore, an error feedback control approach could be added in parallel, which requires a real-time model of the vehicle system, which is used to compare the actual operation to the desired. In this type of system, the network would respond to error and provide the necessary change in order to meet the ideal operation, which would be added in parallel to a system controlling the overall operation and control. Due to the limitations in real-time processing and a lack of
initial training data neural network approaches are rare, but show a promise in successful
tests and simulations to meet optimization goals accurately in very non-linear control.

2.4 Driveability

Driveability is a complex part of vehicle operation and encompasses many metrics from
smooth operation to response speed and sensitivity. In the current automotive market
driveability is extremely important with a need to impress consumers with performance
and drive quality.

2.4.1 Metrics and Measurements

Most measurements of driveability are based on objective opinion or review of vehicles.

In many cases objective opinions can be correlated to a physical measurement of
acceleration signals and response delays. However, many other metrics remain objective.
Table 2 shows a vehicle drive appraisal test conditions, which would be rated.
Table 2: Vehicle Drive Appraisal - Test Conditions [15]

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Rating</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start quality</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Idle stability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Idle NVH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Idle drive</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pullaway</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tip-in/ back-out (City)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tip-in/ back-out (Highway)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cruise 2000/ 3000 rev/min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full load performance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accel from low to high speeds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pedal response</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gearshifts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine response in neutral</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3 shows many of the criteria being evaluated and measured in a vehicle test for driveability.

Table 3: Driveability Metrics and Observations [15], [16]

<table>
<thead>
<tr>
<th>Driveability Metrics</th>
<th>Driveability Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Interior noise level</td>
<td>• Stumbles</td>
</tr>
<tr>
<td>• Acceleration RMS value</td>
<td>• Oscillations</td>
</tr>
<tr>
<td>• Vibration dose value</td>
<td>• Overshoot</td>
</tr>
<tr>
<td>• Acceleration/deceleration jerk</td>
<td>• Prolonged response</td>
</tr>
<tr>
<td>• Maximum transient vibration value</td>
<td>• Hunting and roughness</td>
</tr>
<tr>
<td>• Tip-in/tip-out response</td>
<td></td>
</tr>
</tbody>
</table>

Additional metrics are those developed by companies such as AVL where algorithms associated with driver commands and accelerometer readings determine the quality of pedal response. Lastly, companies such as GM develop internal rating systems for interior/exterior noise and suspension response for benchmarking vehicles.
2.4.2 Controls for Driveability

Driveability while extremely important to a final vehicle released rarely has a specific function or algorithm devoted to optimizing driveability. Instead, driveability is typically achieved by careful calibration, design, and additional control rules. In this way outstanding driveability is achieved, but not in the same way efficiency is optimized by an algorithm.

Software employed to improve driveability includes a variety of algorithm modifications and additions. In one case, considering a shift hysteresis and speed matching might help reduce jerk and oscillations. In other cases, a filter might be applied during all operation in order to smooth oscillations in signals in or out of the control. Many controls can also harm driveability, such as filters and rate limits adding delay or lag to the system response. Also, often efficiency algorithms must be restricted in order to prevent drastic jumps or rapid oscillations. These examples all relate to vehicle operation while at speed and the algorithm or calibration considerations taken for this operation, but another region important to driveability is low speed maneuvers such as creep torque, braking torque, and pedal sensitivity. In these operations, matching a conventional automatic vehicle is often a driver’s preference, which means a hybrid would have to offer a simulated creep torque typically provided by the torque converter. At the same time this simulated creep torque robs energy when the vehicle is stopped and therefore, must be blended in and out. For braking at various speeds the driveability requires fading of the regenerative braking in order to smoothly approach a stop.
CHAPTER 3

ECOCAR TEAM DEVELOPMENT AND MANAGEMENT

3.1 Introduction
The EcoCAR Competition strives to not only design and build advanced vehicles for competition, but most importantly train young engineers and business students for future work in the industry. Promoting development of a team accomplishing these goals is a large leadership responsibility. The vehicle design, development, and construction require multi-disciplinary project groups with various goals and skills. In addition, a business and outreach element helps to promote energy efficiency, technology, and sponsorship, which requires business, education, communication, photography, and financial students to also partner with the vehicle development part of the team. In the end this diverse team operates much like a small corporation.

3.2 Recruitment
First and foremost in team development is to recruit students to join the program. The concept is simple in the need to attract the highest caliber members and retain them.
3.2.1 Engineering Recruitment

Recruiting students often varies based on the type of students and opportunities offered by the university. In the case of Ohio State University, involvement fairs are organized to give clubs and teams an opportunity to attract new members. These events provide a large crowd to publicize the program, but usually are not the critical motivation or event bringing students to the team. First, the engineering students are similar to any student and drawn by excitement, enthusiasm, and a bit of sales for benefits of membership. However, a successful engineering team member is drawn by the challenge and a deep interest in what the design and development work provides. For example, a certain member might be drawn by a concern for the environment, which can be satisfied by pursuing the goal of creating a more efficient vehicle.

An important method in recruitment is to exercise well structured connections, which are usually professors and veteran team members identifying high caliber students and pointing them to the program. Additionally, a team aspect that attracts students is an ambitious and challenging project, which provides a contagious excitement for students and professors to present to new recruits.

Besides how to recruit members, the type of members is also critical. A goal to recruit members as freshmen and sophomores helps to maintain continuity, but also gives members a chance to be trained and learn much of the skills and design required to be successful through the remaining time on the team.
3.2.2 Business/Outreach Recruitment

Recruitment of a business and outreach team shares many of the same techniques with engineering, such as excitement, enthusiasm, and using connections. However, the goals of recruitment vary due to the tasks. Typically, a diverse group in age, major, and background offers the greatest success, by offering a wide variety of ideas. Also, targeting people with a competitive nature, which will work hard to win and prove excellence, is essential to the team’s motivation.

3.3 Team Management Structure

Managing a team of thirty plus students requires planning and a structure matching the talent and skills of the leaders. Identifying leadership, management, and projects are all first and foremost. Secondly, knowing the limits of one’s time, leadership, and management is also important.

3.3.1 Structure of Leadership

Leadership and management are quite different in purpose, but important to a successful team. Having one central leader identified as the contact carries many roles and, therefore, can be structured in various ways based on skills and needs. First, a long term single leader provides continuity and a known source of answers, contact, and motivation, which benefits in making management simpler. For management, the one person, as a leader, coordinates questions, answers, and contacts. Additionally, the one leader shares responsibility for the decision process with sub-leaders, but has the ability to draw on past experience and wisdom. Figure 8 shows the team organizational chart, which has the management structure of one team leader, but shares the decision making
and leadership with two sub-leaders seen at the top of the structure. This shared leadership for the organizational structure shows a central leader and contact as the team leader, but represents a hierarchy for decision making. The EcoCAR team structure also, distributed leadership to the sub-leaders where possible to relieve burdens. For this distribution, the central leader was identified along with sub-leaders managing specific aspects of the team. As shown in the organizational chart, management structure and organization is based on decisions to be made for the team. Therefore, certain sub-leaders are elevated in the organizational structure to manage aspects of team leadership such as team travel (team radar). The team management is based primarily on experience with the respective group or project, but leadership is a skill brought out in teamwork, which is typically a combination of people, time, and project management. Leadership is directed by the team leader and the sub-team leaders, which must guide, motivate, and inspire the entire team or sub-team.
3.3.2 Project Timelines

Managing project timelines is important to meeting goals, but must be done efficiently to be a help rather than hindrance. Therefore, project timelines have three primary goals:

1. Coordination between all project groups for work on the one vehicle.
2. Identifying supplies and anticipation for part lead times.
3. Completing sequential tasks in proper order and providing time needed for each task.

These goals guide setting and managing project timelines with the group of team leaders. During meetings of the entire team, status updates and task assignments are given. Budgeting appropriate time and pushing for ambitious goals is important to allow for mistakes and delays in the timeline.
3.3.3 Training

Preparation for projects and work is very important to any program. Doing training and providing a knowledge necessary for tasks early helps to get a strong knowledge base established early to not burden leaders and more knowledgeable members with training members individually for projects. Training can be done both within the team by training how to use equipment such as the vehicle lift and machine shop milling machines and lathes, but other training is done by the EcoCAR organization. This internal team training can be done in large groups to review overall operation, but also is well done by establishing mentoring for new team members to be coached through initial projects by experienced team members. The next type of training, done by the competition and sponsor companies, prepares teams for challenges of the competition. In this competition training, it is important for the team to bring a mix of experienced and inexperienced members, which allows the team to train new members on basic knowledge, but also learn advanced topics with experienced members. These different training methods all rely on team members sharing knowledge to expand the knowledge base of the team quickly and early in the program to prepare for future projects.

3.4 Project Teams

In industry and many different groups work is divided based on projects, and success relates to the group, structure, goals, and communication. The EcoCAR project teams often need elements from different expertise in order to complete the project. Therefore, project groups are divided in much the same way as industry with various majors or levels of experience to accomplish the different tasks.
3.4.1 Team Composition

Project teams are diverse in both background and discipline or specialty. In this way, considerations and communication is much more direct between different aspects of the design and vehicle. The multi-disciplinary teams are able to accomplish the project with greater knowledge of how it will influence the other aspects associated. An example is when making the case for an electric motor the design is primarily mechanical, but a member on the project is electrical and can provide insight to electrical connections that are made through the case. In the end, the design requires less revision when presented to the entire group or implemented in the vehicle because considerations were made on all aspects of the design during the process.

3.4.2 Mentoring

Mentors offer a vital role in project teams or groups. Typically the mentor is one individual on each project team, but in other cases they might be recognized as a resource from another team if questions arise. Identifying a mentor when establishing a project team helps to provide a resource for knowledge and guidance as the project progresses. The mentor can also be in some cases one identified for the team from industry such as General Motors or dSPACE, which typically offer technical support during the EcoCAR competition. The mentors help to ensure projects progress with the necessary resources to answer questions and prevent unnecessary mistakes.

3.4.3 Detailed Goals

Goals are important at every level of teamwork and projects, but in smaller project teams detailed goals are possible, where as reporting progress or completion for a generic goal
such as electrical wiring is not possible. In the project teams, detailed goals are set to provide a road map to vehicle completion or operation. For example, in the transmission design it is possible to set a deadline for CAD completion, which is followed by a deadline for a machining quote and delivery of a machined part. Then, the transmission assembly and installation can all be managed with deadlines for the same group and project team. Lastly, goals like parts or supplies procurement deadlines can be added to ensure goals are met in the necessary timeline.

3.4.4 Time and Resource Management

Meetings and resources for a non-profit, semi-volunteer team can be scattered and difficult to manage efficiently. The project team atmosphere provides a well laid framework for managing meetings and resources, which starts with the ability to have detailed meetings with a project team only in addition to larger group meetings. This allows resources to be shared between project groups by staggering meetings or in other cases for information to be shared by having common meeting times. For example, two project teams existed one for the transmission and one for the clutch system, however, with common interfaces shared meeting times were required to share information. Later, in development, the two project groups required the same equipment to accomplish construction and began to split work time and meetings in order to share resources.
3.5 Motivation and Retainment

Motivating a team of students, volunteers, and graduate students requires knowledge of member goals, leadership, and access to benefits such as jobs. Many team members have varying levels of interest, commitment, and goals.

3.5.1 Job Placement

The first and foremost motivation for team members is to get high level job opportunities and placement. During EcoCAR, the current economic climate in the automotive industry showed a small number of opportunities, but required high caliper students and engineers. Therefore, providing networking from the EcoCAR competition level, and keeping students informed of opportunities by passing on information was not only important, but a responsibility of the team leaders. Additionally, recommendations and encouragement of jobs often comes from a team leader and helps to ensure students have access to job opportunities and interviews, but also recognize how experience applies to involvement. As veteran team members acquire jobs and placement in the industry younger members also become committed to achieving the same level of success in the team and with job opportunities. This overall networking and encouragement process in job placement yields measureable results in the end of the program.

3.5.2 Application of Classwork

Competition teams such as EcoCAR can have a variety of relationships to the classroom depending on the curriculum. However, regardless classwork can be applied in many ways to the EcoCAR project primarily based on the real application of the project as a whole and the variety of applications within the vehicle project as a whole. In this way
simply discussing relationships with certain areas of study allows much greater interest in
the classroom as well as greater interest in certain projects after seeing how classwork
might be used to develop or improve the vehicle. Applying classwork helps to concrete
studying and ensure it is known that both work on the project and classwork are useful to
degree development and knowledge.

3.5.3 Career Goals
Career goals are the primary motivation for a college degree and college decisions,
therefore, work on the EcoCAR team or a competition team should tie directly to career
aspirations. This is not possible in all cases, but places a good goal for leadership
directions. In the competition team typically not all possible options are explored,
therefore, allowing options of interest to each member is achievable as the team grows
and fills necessary needs for development and construction. For example, a desire to do
design work with displays or panels is just as useful as weight reduction. When the work
is chosen based on desire the project is given more effort, time, and enthusiasm, which
can far exceed the mediocre work done on a project of slightly higher relevance.

3.6 Conclusion
Team leadership and management vary greatly from project to project, industry to
university, and with different skill sets. However, in any case enthusiasm, excitement,
and mood are contagious, but also presenting challenges as an opportunity to prove
prestige and success adds passion for the project. In the case of the OSU EcoCAR Team,
the challenges were enormous and the team diverse in skill, background, and knowledge,
but channeled into every project was an excitement to see the completed product perform. In this team, the success and performance can be attributed to many factors, with one being the role of multiple skilled leaders and another being many people passionate and excited about the team’s work.
CHAPTER 4

VEHICLE DESIGN AND DEVELOPMENT OVERVIEW

4.1 Introduction

The EcoCAR development process has been outlined briefly in Chapter 1, where it is explained the development begins with preliminary architecture development and determining the performance targets. In year 1, the Ohio State team brainstormed to develop three architectures for comparison and assessed comparisons based on criteria such as: performance, educational benefit, and ability to drastically reduce fuel consumption. The architecture selection ranking is shown in Table 4, with the lowest number being the best.

Table 4: Decision Matrix used to Rank Vehicle Architectures

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weighting of Criteria</th>
<th>2-Mode with Electric Rear</th>
<th>Series</th>
<th>Series with Twin Clutch Final Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (kg)</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Efficiency (City)</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Efficiency (Hwy)</td>
<td>9</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>0-60</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Education Value</td>
<td>10</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Risk</td>
<td>5</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Cost</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Packaging</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Component Availability</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Facilities Requirements</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Scoring: 1 is best

Weighted Total: 101 93 89

Rank: 3 2 1
The ranking of vehicle architectures shows the emphasis the team placed on educational value, efficiency, and performance. These aspects capture the primary EcoCAR goals of training engineers to achieve outstanding performance and efficiency, but, also, ensuring that challenges are introduced in the design to truly study and learn hybrid vehicle design. This chapter will outline the progression of the design and development from conception to final completion for the OSU EcoCAR vehicle architecture. Then the details of the final design will be reviewed specifically focusing on those designed by the team.

4.2 Vehicle Architecture Progression

The Ohio State team leveraged research and experience in diesel engines, parallel hybrids, many previous advanced vehicle competitions, and a literature review in the initial architecture brainstorming. Being a competition, there was also an analysis of competition points to consider the success of many alternatives.

The architecture selection began with an industry, research, and consumer driven goal to produce a car with a large plug-in range. In most discussion with consumers a plug-in range would be most desirable if all electric, which provides a choice between using fuel and not using fuel simply by remaining within the vehicle’s electric range. Next, there was a goal to produce a vehicle with no compromises providing both performance and fuel economy in all modes. This architecture type began to emerge as a comparison of a series architecture to a parallel architecture was reviewed. A series architecture would offer equal performance in both charge depleting and charge sustaining, but degraded fuel economy in highway charge sustaining. A parallel configuration would have degraded performance in charge depleting, without engine operation, but improved
charge sustaining fuel economy and performance. In this way, architecture capable of merging series and parallel elements in the most critical operating regions was developed. The system still balances trade-offs, such as only a single gear to minimize complexity and risk. Figure 9 shows the initial series concept and Figure 10 shows the developed concept of a series and parallel capable system. The developed system provides the benefits of a series system and a parallel system by allowing series operation at low speeds and parallel operation at high speeds. This functionality utilized series and parallel operation well without a complex architecture and transmission gearset.

Compared with a series only system, the concept allowed engine torque to bypass electrical losses and power the wheels directly, which could improve highway fuel economy in charge sustaining operation by as much as 20 percent. Next, this concept allowed a decoupling of the electric machine from the engine which would dramatically improve performance during charge depleting operation over a series or parallel system with no access to the generator and/or engine. Table 5 summarizes the advantages and disadvantages of this architecture.
Table 5: Twin-Clutch Architecture Advantages and Disadvantages

<table>
<thead>
<tr>
<th>Advantages:</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Higher all electric performance without adding more electric propulsion.</td>
</tr>
<tr>
<td>- Higher highway fuel economy in charge sustaining operation.</td>
</tr>
<tr>
<td>- Access to electric drive on front axle should anything fail on rear</td>
</tr>
<tr>
<td>electric drive.</td>
</tr>
<tr>
<td>- Engine only capability on highway if electric operation is faulty or</td>
</tr>
<tr>
<td>battery is not capable.</td>
</tr>
<tr>
<td>- Series only operation, should final drive or clutch two not function</td>
</tr>
<tr>
<td>properly.</td>
</tr>
<tr>
<td>- Higher education value</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Disadvantages:</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Higher mechanical complexity</td>
</tr>
<tr>
<td>- Higher risk, with more components to fail</td>
</tr>
<tr>
<td>- Higher controls complexity</td>
</tr>
</tbody>
</table>

4.2.1 Transmission Development Progression

Figure 11 shows a concept for a dual clutch transmission system allowing the multi-mode operation desired for the EcoCAR vehicle. Development of gear ratios and component selections were vital to the success of this system. Initially, a concept was developed using gear ratios found by simulation of the hardware available.
Figure 11: Initial Transmission Layout Schematic

Figure 12 shows a comparison of normalized gear ratio adjustments as related to performance and Figure 13 shows a comparison of normalized gear ratio adjustments as related to fuel economy. The normalized value of one for gear ratio corresponds to a total gear ratio of 2.65 from engine crankshaft to the axle, which was later chosen by gear sets available.
Besides gear ratio, packaging and available electric machines dictated hardware design as well. The design concept, also, included a belt coupling the electric machine to the clutches, which was studied and optimized for series generating. Figure 11 shows the initial layout schematic of hardware to implement the concept and Figure 14 shows the CAD model designed to package the available hardware and implement the system. This initial system used custom cases and interfaces for the electric machine and two independent dry clutch systems with generic off the shelf gears. The CAD design proved
the system was physically possible, but revealed many high risk components and hardware. First, load ratings, linear speed ratings, and size of the belt system were in question. Second, location of the electric machine offered very little clearance, and third, the clutch system would require custom shafts and actuators. Lastly, gear strength and efficiency was unknown without testing or extensive analysis.

![Figure 14: CAD Model of Initial Transmission and Clutch System Design](image)

With the many questions and risks, the development entered the second year of the EcoCAR development process and began detailed design and component procurement. First, in this process was the replacement of the electric machine with a smaller more capable permanent magnet machine, which provided a packaging improvement. Next, advice was sought from the Ohio State gear lab for gearing of proper ratio, strength, and efficiency for the application. The resulting conclusion was the near proper ratio is commonly available as the final drive gears in most front wheel drive manual and automatic transmissions on the market. These would have strength and efficiency equal
or exceeding what was required as proven by manufacturer durability and specifications. Next, design consultation was sought from the manufacturer (Goodyear) for an available belt system to be sized for speed, power, and torque requirements. The summary for analysis performed by Goodyear to select belt size for this application is given in Appendix A. Lastly, research in clutch systems showed a dual dry disk clutch system was available as a single unit with a matched mechanical actuator system. These components lead to a major design improvements and modifications.

The modifications made were to accommodate hardware and component changes, but also increased detail in design, mounting, and packaging. First, due to the clutch system change, the system schematic was changed as seen in Figure 15 where the clutch housing and pressure plates are driven by the electric machine and the two disks are connected to the engine and transmission respectively.
Figure 15: New Transmission and Clutch System Schematic to Accommodate Component Improvements

Adding to this schematic layout changes to the components resulted in the following CAD model shown in Figure 16. The CAD model required three project groups totaling nine to ten people to complete. This resulted in exact CAD models including clearances, tolerances, service access points, lubrication lines, and proper alignment pins.
4.3 Architecture Details

The OSU EcoCAR design has a large amount of custom hardware, which was designed and built by the team. A review of the system will show the design considerations, the final hardware built, and what it accomplishes.

4.3.1 Dual Clutch Transmission Overview

The dual clutch transmission is at the heart of the OSU EcoCAR design; therefore, understanding functionality and specifications is vital to understanding controls and vehicle operation. The system includes many elements of hardware, as well as actuators, much of which have been previously described in development sections. Figure 15 and Figure 16 above show the schematic and CAD of the system respectively, which were also explained with the system development progression. Figure 17 shows the cutaway CAD model of the dual clutch transmission system, yellow shows components always
spinning with the electric machine, green shows the components spinning with the
gearbox or engaging the gearbox, and violet shows the engine shaft line and engagement.
The transmission system provides the vehicle with three distinct hardware modes changed by actuators and software. The first configuration, shown in Figure 18, connects
the front electric machine (FEM) to the wheels through engagement of the second clutch disk to the single speed gearbox (green in Figure 17). This offers the extra acceleration performance and all wheel regenerative braking. An additional benefit is a lower gear reduction on the front axle as the ratio found on the rear axle, which properly managed, can provide options to boost highway efficiency for the electric machines.

Figure 18: Charge Depleting Mode with FEM Only Engaged to Wheels

The second configuration, shown in Figure 19, connects the FEM to the engine through engagement of the first clutch disk only (violet in Figure 17). This offers engine cranking as well as a charge sustaining series operation with the engine and FEM as a generator unit for the vehicle.
The third and last configuration is shown in Figure 20, in which, both clutch disks are engaged, which connects the FEM to both the engine and gearbox. This mode provides a mechanical connection from engine to wheels through the clutch gearbox system, which drastically improves highway fuel economy by minimizing series conversion losses. This mode is restricted to only operation at allowable engine speeds as they correspond to wheel speed through the gearbox.
To best summarize the transmission and clutch system Table 6 shows the specifications of all the components making up the transmission system.
### Table 6: Summary of Transmission System Specifications

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification Type</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gearbox</td>
<td>Origin of Gears</td>
<td>GM MH2 Automatic Transmission</td>
</tr>
<tr>
<td></td>
<td>Gear Type</td>
<td>Helical</td>
</tr>
<tr>
<td></td>
<td>Total Ratio</td>
<td>2.77:1</td>
</tr>
<tr>
<td></td>
<td>Oil Type</td>
<td>Dextron III or higher (ATF)</td>
</tr>
<tr>
<td></td>
<td>Differential Type</td>
<td>Open Bevel Gear</td>
</tr>
<tr>
<td></td>
<td>Case Material</td>
<td>Aluminum</td>
</tr>
<tr>
<td>Belt Drive</td>
<td>Make</td>
<td>Goodyear Eagle Pd</td>
</tr>
<tr>
<td></td>
<td>Type</td>
<td>Herringbone Tooth (8mm pitch)</td>
</tr>
<tr>
<td></td>
<td>Material</td>
<td>Kevlar Braided Rubber</td>
</tr>
<tr>
<td></td>
<td>Ratio</td>
<td>1.5:1</td>
</tr>
<tr>
<td>Clutch System</td>
<td>Make</td>
<td>Luk</td>
</tr>
<tr>
<td></td>
<td>Type</td>
<td>Dual Dry Disk</td>
</tr>
<tr>
<td></td>
<td>Torque Rating</td>
<td>250 Nm</td>
</tr>
<tr>
<td></td>
<td>Pressure Plate Type</td>
<td>Normally Disengaged</td>
</tr>
<tr>
<td>Actuator System</td>
<td>Make</td>
<td>Thomson Linear</td>
</tr>
<tr>
<td></td>
<td>Type</td>
<td>Electric Linear Actuator</td>
</tr>
<tr>
<td></td>
<td>Stroke</td>
<td>2 in</td>
</tr>
<tr>
<td></td>
<td>Max Force</td>
<td>250 lbf</td>
</tr>
<tr>
<td></td>
<td>Lead Screw Type</td>
<td>Acme</td>
</tr>
<tr>
<td></td>
<td>Maximum Travel Speed</td>
<td>2 in/s</td>
</tr>
<tr>
<td></td>
<td>Position Feedback Type</td>
<td>Quadrature Encoder</td>
</tr>
<tr>
<td></td>
<td>Controller Type</td>
<td>Smart H-bridge</td>
</tr>
<tr>
<td></td>
<td>Voltage</td>
<td>12 V</td>
</tr>
<tr>
<td>Electric Machine</td>
<td>Manufacturer</td>
<td>Remy International</td>
</tr>
<tr>
<td>(FEM)</td>
<td>Type</td>
<td>3-Phase Permanent Magnet</td>
</tr>
<tr>
<td></td>
<td>Cooling</td>
<td>Dextron III or higher (ATF)</td>
</tr>
<tr>
<td></td>
<td>Power Rating</td>
<td>82 kW Peak</td>
</tr>
<tr>
<td></td>
<td>Torque Rating</td>
<td>325 Nm Peak</td>
</tr>
</tbody>
</table>

Use of the summarized hardware and components could be optimized in a variety of ways. First, a reduction in the size of the final drive gears would reduce weight and likely provide sufficient strength. This is based on a significant reduction in output torque from the original transmission application. Second, a more reliable and permanent solution to the coupling from the electric machine to the clutch system would be a helical gearset. However, the belt system is reliable, quiet, and simple, which was best for a low
budget prototype. Lastly, a reduction in the electric machine size or an increase in clutch rating would either reduce weight and cost or increase performance. Instead, the current system requires software torque limiting to prevent clutch slip and, therefore, wastes roughly 30% of the electric machine torque capability. Finally, the as built system proved a well designed initial prototype and proof of concept for a versatile architecture system.

4.3.2 Battery System

The EcoCAR team investigated multiple battery manufacturers and cells before arriving at a final pack selection. Selection was largely driven by budget and technical support, however, the battery pack was compared with others based on criteria such as: internal resistance, energy per weight, energy per volume, and cooling capability. The final battery pack selected met or exceeded simulated needs and requirements. Table 7 summarizes the high voltage battery pack system selected.

<table>
<thead>
<tr>
<th>Specification Type</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>A123 Systems</td>
</tr>
<tr>
<td>Chemistry</td>
<td>Lithium Iron Phosphate</td>
</tr>
<tr>
<td>Cell Type</td>
<td>Prismatic Pouch</td>
</tr>
<tr>
<td>Nominal Voltage</td>
<td>360 V</td>
</tr>
<tr>
<td>Maximum Useable Energy</td>
<td>21.3 kWh</td>
</tr>
<tr>
<td>Amp Hours per Cell</td>
<td>20 Ah</td>
</tr>
<tr>
<td>Pack Configuration</td>
<td>5 Series Modules</td>
</tr>
<tr>
<td>Module Configuration</td>
<td>3 Parallel Cells in 22 Series Sets (66 cells total)</td>
</tr>
</tbody>
</table>

The high voltage battery system had to be packaged, cooled, wired, and vibration isolated. The system packaging designed was split into two packs in series with liquid cooling and both electrical isolation inside the pack and vibration isolation externally by
mounting both packs on rubber mounts. The pack designed in CAD is shown in Figure 21, which shows three modules are in the rear of the vehicle and two modules are in the front.

![High Voltage Battery Pack](image)

**Figure 21: Vehicle and Battery CAD Layout**

The split pack was chosen in order to better balance weight and minimize the cargo space consumed by the battery packaging.

### 4.3.3 High Voltage Electrical System

Regardless of packaging the high voltage electrical system must be sized to accommodate power, protect components, protect wiring, and maintain safe operation. Wiring and fusing was designed based on worst case loads and conditions and in some cases given an additional safety factor that with testing could eventually be removed. The simulations deemed worst cases were towing and US06 drive cycles, which were run to determine the root mean squared (RMS) electrical load, which was used to size wiring and fusing for the high voltage electrical system. shows an early simulation of the AC current for 3-
phase wiring over the US06 cycle for the rear electric machine (REM) and Figure 23 shows an early simulation of towing for REM only operation.

Figure 22: Rear Electric Machine AC Current During US06 Simulation

Figure 23: Rear Electric Machine AC Current during Towing (REM Only)
Figure 24 shows the battery current for the US06 and towing cycles, which shows a significantly greater requirement for towing when considering continuous current.

![Battery RMS Current for US06 and Towing Cycles](image)

**Figure 24: Battery RMS Current for US06 and Towing Cycles**

Based on simulation of worst case currents during simulation, safety factors, and capability for handling peak current operation the high voltage system shown in Figure 25 was developed. The battery cables and connectors external to battery packs all use Yazaki cable that provides a braided shield with a minimum of 30 dB shielding (based on Yazaki specifications). Wire routing and connections were designed and implemented by the team, but battery contactors, battery monitoring, and current measurements are all provided by A123 systems. Therefore, the system offers a reliable, low interference, power capable system and the system is protected to the minimum rating of all electrical wiring.
4.3.4 Engine

The OSU E-REV engine is another critical element of the vehicle design in order to meet goals and requirements for efficiency and emissions, but also plays a significant role in vehicle controls. The engine selected is a Honda R18A4 1.8L compressed natural gas engine (Figure 26), with the software designed and calibrated by the Ohio State team for dedicated ethanol (E85) usage. This engine’s high compression ratio (12.5:1) takes advantage of the high octane of E85. The engine features a close-coupled, metal foil
monolith, three-way catalytic converter with precious metal group (PGM) loading of 150 g/ft³ Pd and 10 g/ft³ Rh for high catalytic performance. The catalytic converter includes an Emitec electrically-heated catalyst (Figure 27) for improved cold-start performance. This technology is particularly useful for the E-REV architecture because the engine will start cold during mode switches from charge depleting to charge sustaining operation. Ohio State’s engine re-calibration efforts were done on an in-house engine dynamometer (Figure 28).

Modifications to the fuel rail and injectors were made to make the engine capable of running ethanol. To re-calibrate, the team started with a mass-airflow (MAF)-based system, with the rate of air intake being measured by a MAF sensor. Next, testing was performed at steady-state conditions over the operating range of the engine to determine maps for spark timing, volumetric efficiency (VE), and brake efficiency.

Then, a speed-density system was implemented to determine a more accurate air-per-cylinder (APC) estimation during transients. The most important elements of this engine selection to overall vehicle function is its high efficiency, which peaks at >41 percent, its
lightweight, and compact size, and very low noise and vibration. One additional consideration for packaging and efficiency was an electric water pump to schedule the correct flow based on coolant temperature to reduce friction losses as well as reduce the pump’s mechanical losses. The engine also features a dual stage cam and exhaust gas recirculation (EGR). The cam provides a delayed closure timing and profile for increased low power efficiency and the EGR can help reduce pumping losses at low loads.

Therefore, the engine selected provided optimal and reliable hardware for the vehicle design, along with excellent versatility for tuning and optimization.

4.3.5 Vehicle Technical Specifications

During the vehicle development and design simulation and modeling was done to determine the overall expected vehicle performance early in the development. As the development, construction, and testing of the vehicle continued these results serve as a benchmark for minimum expectations of the vehicle. Table 8 shows the predicted performance targets and vehicle specifications as compared with the original vehicle and competition targets.
### Table 8: Ohio State Team Vehicle Technical Specifications (VTS)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Donated Vehicle Platform</th>
<th>EcoCAR Competition</th>
<th>Predicted OSU E-REV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ECOCAR COMPETITION REQUIREMENTS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceleration 0-60 (s)</td>
<td>10.6 s</td>
<td>≤ 14 s</td>
<td>9.9 s</td>
</tr>
<tr>
<td>Acceleration 50-70</td>
<td>7.2 s</td>
<td>≤ 10 s</td>
<td>5.0 s</td>
</tr>
<tr>
<td>Towing Capacity (kg, (lb))</td>
<td>680 kg (1,500 lb)</td>
<td>≥ 680 kg @ 3.5%, 20 min @ 72 kph (45 mph)</td>
<td>1,130 kg @ 3.5%, 20 min @ 72 kph (45 mph)</td>
</tr>
<tr>
<td>Cargo Capacity (mm, (in))</td>
<td>0.83 m³</td>
<td>Height: 457 mm (18”) Depth: 686 mm (27”) Width: 762 mm (30”)</td>
<td>Height: 730 mm (28.7”) Depth: 800 mm (31.5”) Width: 900 mm (35.4”)</td>
</tr>
<tr>
<td>Passenger Capacity</td>
<td>5</td>
<td>≥ 4</td>
<td>5</td>
</tr>
<tr>
<td>Braking 60-0 (m, (mi))</td>
<td>38.43m (123-140 ft)</td>
<td>&lt; 51.8 m (170 ft)</td>
<td>42 m (138 ft)</td>
</tr>
<tr>
<td>Mass (kg, (lb))</td>
<td>1,758 kg (3,875 lb)</td>
<td>≤ 2,268 kg (5,000 lb)</td>
<td>2,109 kg (4,650 lb)</td>
</tr>
<tr>
<td>Starting Time (s)</td>
<td>≤ 2 s</td>
<td>≤ 15 s</td>
<td>&lt; 5 s</td>
</tr>
<tr>
<td>Ground Clearance (mm, (in))</td>
<td>198 mm (7.8 in)</td>
<td>≥ 178 mm (7 in)</td>
<td>168 mm (6.6 in)</td>
</tr>
<tr>
<td>Range (km, (mi))</td>
<td>&gt; 580 m (360 mi)</td>
<td>≥ 320 km (200 mi)</td>
<td>418 km (260 mi)</td>
</tr>
<tr>
<td><strong>ECOCAR COMPETITION TARGETS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Consumption, CAFÉ Unadjusted, Combined, Team: UF Weighted</td>
<td>8.3 l/100km (28.3 mpgge)</td>
<td>7.4 l/100km (32 mpgge)</td>
<td>4.3 l/100km (54 mpgge)</td>
</tr>
<tr>
<td>Charge Depleting Fuel Consumption</td>
<td>N/A</td>
<td>N/A</td>
<td>0 l/100km (ge)</td>
</tr>
<tr>
<td>Charge Sustaining Fuel Consumption</td>
<td>N/A</td>
<td>N/A</td>
<td>8.8 l/100km(ge)</td>
</tr>
<tr>
<td>Charge Depleting Range (km, (mi))</td>
<td>N/A</td>
<td>N/A</td>
<td>64.4 km (40 mi)</td>
</tr>
<tr>
<td>Petroleum Usage (kWh/km)</td>
<td>0.85 kWh/km</td>
<td>0.77 kWh/km</td>
<td>0.10 kWh/km</td>
</tr>
<tr>
<td>Emissions</td>
<td>Tier II Bin 5</td>
<td>Tier II Bin 5</td>
<td>&lt; Tier II Bin 5</td>
</tr>
<tr>
<td>WTW GHG Emissions</td>
<td>250 g/km</td>
<td>224 g/km</td>
<td>210 g/km</td>
</tr>
</tbody>
</table>

* Higher towing capacities have not been tested.

These vehicle technical specifications include specific goals set by the team for an all electric range, which was accomplished in the vehicle architecture selection and design.
4.4 Conclusion

The designed vehicle hardware and selected components provide an excellent platform to meet the goals and requirements set by the team for the vehicle performance and fuel economy, but the system also provides extraordinary controls optimization and research versatility. The development process of the hardware design and system took a long path from conceptual designs to final CAD models used for CNC machining, but time, considerations, and attention to detail prevented redesign of the final hardware constructed. In the final year, the EcoCAR vehicle hardware was refined primarily in assembly and construction details and not the design of hardware, which was crucial to success by offering more time for tuning and optimization. The vehicle design and hardware met or exceeded the design goals, expectations, and proved reliable, which was achieved by including factors of safety and seeking advice from engineers with experience in these automotive systems.
CHAPTER 5

SUPERVISORY CONTROL SYSTEM

5.1 Introduction
The supervisory control of the EcoCAR E-REV is vital to vehicle operation by managing all torque, speed, power, and driver commands as well as the energy management. In this vehicle, the supervisory control is responsible for optimizing how the vehicle uses components and energy sources in the most efficient way possible to maximize performance and minimize fuel consumption.

5.2 Controls Hardware Architecture
The OSU EcoCAR vehicle uses a dSPACE MicroAutoBox (MABX) for the supervisory control, which offers a large memory and processor to enable complex calculations and creative control systems without being limited by hardware performance. The dSPACE MABX model chosen was a MABX1401/1505/1507 this model designates a 1401 chassis with an expansion of inputs and outputs, therefore the controller offered four Controller Area Network (CAN) channels as well as dozens of digital and analog inputs and outputs. The controller does not offer high current capability on any outputs, which means low level control requires additional circuits or systems, which reinforces the choice to use the controller for supervisory control and not low level control.
The control system architecture places the dSPACE MABX hierarchically above all other controllers, such as the engine, battery, electric machines, and body controllers. In order to manage this structure and these controllers, the vehicle uses four CAN networks to interface all controllers back to the supervisory controller. This structure is shown in Figure 29 where the connections and layout of the vehicle can be seen as well as the control hierarchy.

The control structure used CAN communication between controllers due to a need for reliable, high thru-put communication for control and feedback signals to be transmitted. The CAN communication also offers connectivity to multiple devices on the same network as well as the minimum amount of wiring and hardware connections. Therefore, with this controller hardware and architecture the supervisory control can be implemented easily, reliably, and meet goals and requirements for control management and operation.
5.3 Control Software Architecture

The supervisory control architecture includes a number of levels and sections to its structure. First, the structure includes a traditional controller structure, which means a flow from raw input signal to input conditioning to control algorithms to output conditioning and output signals. Second, the structure includes certain aspects to the control algorithm, which begins with a rule based set of modes and switches and transitions between modes. Finally, the algorithm sets a certain type of operation and management structure based on each mode of operation, which includes a wide variety from startup and shutdown sequencing to electric, charge depleting operation and engine on, charge sustaining operation.

5.3.1 Rule-based Modes

The supervisory control algorithm is divided into distinct operating modes that handle the following cases.

1. Exceptions to the normal vehicle operation
   
   a. Startup Sequence
   
   b. Shutdown Sequence
   
   c. Charging

2. Distinct changes in vehicle hardware configurations
   
   a. Charge Depleting All Electric
   
   b. Charge Sustaining Series
   
   c. Charge Sustaining Parallel
These modes were chosen since the operational algorithm would be distinctly different in each case. The decision to use rule-based control for the mode decisions is based on a clear set of conditions, thresholds, and signals that outline which mode is to be chosen at a given point during vehicle operation. The modes and transitions for overall vehicle states can be seen in Figure 30 and the transition conditions can be seen in Table 9. The normal vehicle “On” modes of operation can be seen in Figure 31 – Figure 34 with the transition conditions.

![Figure 30: Vehicle Mode State Flow](image)

### Table 9: Vehicle Mode State Transition Conditions

<table>
<thead>
<tr>
<th>Transition</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAB</td>
<td>Startup Complete = 1</td>
</tr>
<tr>
<td>SBC</td>
<td>Key State = Off</td>
</tr>
<tr>
<td>SCD, SBD, SAD</td>
<td>On Plug = 1</td>
</tr>
<tr>
<td>SDA</td>
<td>On Plug = 0 &amp; Key State ≥ Accessory</td>
</tr>
<tr>
<td>SDC</td>
<td>On Plug = 0 &amp; Key State = Off</td>
</tr>
</tbody>
</table>

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Besides these modes and conditions described above, the rule-based control of the OSU EcoCAR vehicle also includes a conditioning set of modes for gear selector state. In these modes, the torque commands and clutch states are conditioned to change direction and engage or disengage to provide Park, Reverse, Neutral, and Drive independent of battery and engine state. In this way, safe operation can be ensured regardless of the preceding algorithm function. In the end, all the modes, conditions, and transitions provide a straight forward division of operation to provide safety, sequencing, and proper algorithm division for the best vehicle operation possible.
5.3.2 Charge Depleting Energy Management

The algorithm managing the charge-depleting mode is responsible for taking a driver commanded torque and determining the safest, most drivable, and most efficient way to execute it. In this mode, the system has access to both the front and rear electric machines and the driver can command either positive (acceleration) torque or negative (braking) torque. Multiple algorithms were attempted for this operation, which began with one deemed safe, reliable, and drivable to commission the vehicle. This initial algorithm split the driver’s command equally between the front and rear electric machines, but lacked any consideration for efficiency. Vehicle simulation of primarily energy consumption allowed development testing to ensure all requirements and goals were met in algorithms as they were created and developed. This simulation was used to compare three strategies or algorithms. The first was the simple proportional used to commission the vehicle and as a benchmark for improvement. The second was a power minimization strategy, which takes the instantaneous power consumption of the electric machines and compares all the possible splits capable of meeting the driver’s request and selects the minimum. The third algorithm was developed by intuition that across a broad range the front electric machine has higher efficiency and therefore, this algorithm delivers all torque with the FEM until exhausted and then provides all remaining torque with the REM. Figure 35 – Figure 37 show the results of the battery SOC used compared over three cycles.
Figure 35: FHDS Cycle Simulation Comparison of Three Control Algorithms

Figure 36: FUDS Cycle Simulation Comparison of Three Control Algorithms
The results of simulation across the US06, FHDS, and FUDS cycles shows that the best algorithm for efficiency (uses less battery SOC) is either a power minimization strategy or a simple strategy using intuition. However, the most versatile algorithm for efficiency improvements is the power minimization strategy, which performed well in all cycles. In this simulation, the final goal of driveability is not addressed, but will be further investigated in Chapter 6.

5.3.3 Series Energy Management

The algorithm for the series operation is responsible for operating the engine and FEM generator system at power levels that maintain battery charge while delivering the driver’s torque command with the rear electric machine. This algorithm also requires conditions that would force mode changes under certain circumstances in order to meet the driver’s request in the best method possible. The algorithm regulates power generated by commanding a speed from the generator and a torque from the engine,
which provides the commanded power output for the system. Due to the FEM being disconnected from the front wheels a high torque request of the driver cannot be met, therefore, the system automatically shifts to charge depleting all electric, which is handled as a rule for mode transitions outside the series algorithm. In all electric, the system can momentarily meet the driver’s request and then, returns to series operation when the torque request drops or battery charge becomes too low. There are a variety of structures for the algorithms to determine the power request needed to maintain battery charge. The goals for this part of the algorithm are to be efficient and provide good noise and driveability properties, but also testing reveals reliability or limits on certain types of operation as well. An example of a tested operation limit is overheating can be caused if a high load is requested at zero speed from the engine generator system. Only a few potential algorithms were tested and considered due to time and experience, which included a load following algorithm and an Equivalent Consumption Minimization Strategy (ECMS). The first algorithm for load following calculates the power being consumed by the overall vehicle and requests that power from the engine and FEM generator system, but in this case the generator system cannot deliver the maximum power the vehicle uses during acceleration or other intermittent cases. Therefore, the load following algorithm saturates at these points and uses the battery to supplement extra power consumed. The load following algorithm then replenishes the energy either with regenerative braking or using a PI control to increase the generator power request in lower load situations based on battery SOC tracking a target value. A block diagram shown in Figure 38 outlines the load following algorithm operation and theory.
The next algorithm considered was an ECMS algorithm, which considers the cost in terms of fuel to charge and discharge the battery versus the cost of immediately using fuel to generate the electricity consumed by the vehicle. This algorithm operates based on an equivalence factor for the conversion of electric consumption to fuel consumption, which dictates how the algorithm will track a battery SOC value. An equivalence factor that is too small will cause the system to use more battery energy, which will deplete the battery pack and an equivalence factor too high will cause the system to charge the battery, which will harm fuel consumption. Therefore, tuning of the initial equivalence factor is important, but also created a need to use an adaptive equivalence factor, which increases the equivalence factor as the battery SOC drops below the desired value and decreases the equivalence factor when the battery SOC exceeds the desired value.

Simulation comparing the operating points chosen across a combined efficiency map of the engine and generator set shows both algorithms follow similar trends. These trends include no idle operation of the engine, which means the engine is loaded even at low speeds to maintain higher efficiency operation. Next, another trend is that the operating point quickly increases to high efficiency and high load when more power is required. Figure 39 shows the plotted load following operating points for the engine during series operation over a FUDS cycle simulation. Figure 40 shows the plotted ECMS operating
points for the engine during series operation over a FUDS cycle simulation. Both figures show efficiency contours of the combined engine and FEM system. The final simulation fuel economy and battery SOC is shown in Table 10, which proves operation of both algorithms result in nearly the same fuel economy overall.

Figure 39: Load Following Operating Points for FUDS Simulation
Figure 40: ECMS Operating Points for FUDS Simulation

Table 10: Comparison of Final Consumption Results

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Load Following</th>
<th>ECMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>E85 Fuel Economy</td>
<td>19.73</td>
<td>19.42</td>
</tr>
<tr>
<td>Gasoline Equivalent Fuel Economy</td>
<td>28.56</td>
<td>28.11</td>
</tr>
<tr>
<td>Final Battery SOC</td>
<td>15.26</td>
<td>15.46</td>
</tr>
</tbody>
</table>

Other algorithms could easily be tested for series operation such as a pulse on, pulse off control where the highest efficiency generating point is selected always and the system simply determines the frequency and duty cycle of the system. This could result in higher efficiencies due to no low load operation, but this type of algorithm would likely present driveability concerns and/or requires limits to prevent overheating if pulsed on with vehicle movement for cooling. Another simple algorithm not investigated was a continuous average power generation or slow adapting integral power request to track the...
battery SOC value. This algorithm presents many similar concerns such as driveability and overheating. For these initial reasons as well as time restrictions additional, algorithms such as these were not investigated. The load following algorithm was implemented on vehicle and thoroughly tested, which will be shown in results for this chapter and also shown for driveability. The algorithm was easily tuned to meet efficiency and driveability goals. The ECMS algorithm could have likely also met the same goals, but requires more algorithm development to operate in real-time.

5.3.4 Parallel Charge Sustaining Operation

The vehicle algorithm for charge sustaining operation in the highway is considered a parallel hybrid operating mode. For this mode the vehicle uses the engine, FEM, and REM all in conjunction to power the vehicle as efficient as possible. The result is an algorithm operating the components primarily in parallel. Based on research and investigation of algorithms best for managing this type of operation the ECMS algorithm was selected and optimized for highway driving. In a similar fashion to the ECMS algorithm used in series operation electric consumption is converted to fuel consumption, which is used to determine the cost of using electricity in place of fuel, when the electricity will have to be replenished later in the cycle. In order to instantaneously optimize the fuel consumption with ECMS the system creates a global search region of operating points for two of the three components. Next, these operating points are combined to form a matrix of all the possible combinations of operating points. Thirdly, the matrix of operation points from the first two components is combined with the last component forming an additional matrix of all possible operation points required from
the third device where in each case the combination provides exactly the driver’s requested torque. In this structure, the third and final component is used to eliminate impossible operating points from the search based on its minimum and maximum capable torque. The third and final component also provides the final resolution needed to meet the driver’s request, since the first two components operating points are produced as a discrete set of points. This structure for the ECMS algorithm, as used in EcoCAR, is shown in Figure 41.

![ECMS Algorithm Structure](image)

**Figure 41: ECMS Algorithm Structure**

Testing of the ECMS algorithm revealed using discrete points for the engine and REM, which are then combine with the FEM helps to focus small transient operation on the electric machine instead of the engine. This type of operation improves emissions by relieving the engine of most transient operation where air and fuel dynamics have the most uncertainty. In order to show the impact of engine transient operation on emissions, the wide band oxygen sensor is recorded during a highway drive cycle for two different algorithms. The first, Figure 42, shows the original algorithm, where the engine delivers much of the transient operation and the second, Figure 43, the final algorithm, where transient operation is diverted to the FEM. The data is shown in histograms, normalized around the stoichiometric operation of the engine, which show a narrow distribution for
better emissions control and a wide distribution for more emissions excursions. In addition to the graphical results, the standard deviation of the pre-catalyst oxygen sensor reading was also calculated. The oxygen sensor reading when the engine handles transient operation has a standard deviation of 2.4 percent, whereas, the sensor reading when the FEM handles transient operation shows a standard deviation of only 1.7 percent.
Figure 42: Wide Band Oxygen Sensor Reading Distribution for Algorithm with Engine Transient Operation

Figure 43: Wide Band Oxygen Sensor Reading Distribution for Algorithm with Low Engine Transient Operation
Additional results will be shown further in the chapter as well as given further justification in the following chapter on driveability.

5.4 Transitions

The supervisory control is responsible for managing the driver’s request and the energy of the vehicle in each respective mode, but with this also requires control for transitioning between modes. The supervisory control handled transitions in a few ways in order to provide smooth and seamless changes between modes. First, the control included modes specifically designed to handle transition conditions and changes in control algorithms. Second, the control divided signals in a way that ensured every mode was operating on a consistent set of inputs and delivering a consistent set of outputs. The signals being passed into modes were therefore conditioned for use in all modes, which included the driver signals being converted from a pedal position to a torque command and faults being determined prior to any mode. This ensured the torque command requested was common to all modes and had no inconsistency between modes and available torque. The same conditioning was true after modes where speed and torque requests were always subject to the same rate limits, filters, gear ratio calculations, and saturations, which ensured consistency. The model structure, which provided this signal conditioning
before and after mode operation can be seen in Figure 44.

![OSU EcoCAR Control Strategy Diagram]

**Figure 44: Control Strategy Model Top Level Structure**

The modes created for transitions included two transition modes and a total of four states. The first transition mode was an engine start mode, which will be discussed further in the engine start section. The second transition mode was a transition between series and parallel, which was merged both directions into a single mode based on the action being the same and simply changing direction. The four states included a charge depleting warm-up state, which prepares for the engine start, the engine start mode, a series to parallel transition, and parallel to series transition state. By using the four states signals in the states could anticipate the transition and then trigger when ready or in the series/parallel case indicate the direction of the transition either in or out.

**5.4.1 Clutch Engagement**

The engagement of clutches was an event that required synchronization, time, and fault monitoring in order to maintain safety, reliability, and functionality. The failure of a clutch to engage or disengage was a safety critical operation and therefore required multiple levels of fault monitoring, but also required reliable hardware that could monitor and report position and faults. The hardware chosen was electro-mechanical linear
actuators operated by a smart H-bridge. The electric linear actuators provided accurate position feedback with encoders as well as internal limit switches and overload protection. The smart H-bridges provided control and feedback via a designated CAN connection with the supervisory controller, which accepted control signals for output duty cycle and returned actuator position, controller temperature, input voltage, and fault status. Figure 45 shows the Thomson Linear Electrak Pro actuator chosen to move the clutch release bearings and Figure 46 shows the TI MDL-BDC24 controller reading position and outputting the power operating the linear actuator.

Using the electric linear actuator and DC motor controller the clutch release bearings are moved by levers and linkage systems. Unlike traditional clutch systems the dual clutch chosen requires the actuators to apply force in order to engage the clutch disk, which are roughly 1000 newtons at the lever and between 2700 – 2900 newtons at the release bearing depending on the lever. In addition, the levers move approximately 1.5 – 1.9 inches from completely engaged to completely disengaged. In order for the control system to operate correctly a low level control was implemented on the supervisory
controller that used states to define the status and request of the clutch system and output the proper commands to the clutch controller. The low level control uses position and speed as feedback to move the proper distance and apply the proper force for clutch engagement. During this engagement or disengagement the control also uses time to determine a low level fault has occurred and attempt a reset. This low level control handles the execution of clutch requests.

The supervisory control contains additional clutch monitoring in order to maintain protection beyond the actuator level. This control begins with a prediction of the torque capable through the clutch system on either disk, which uses actuator position and calibrated parameters to estimate the clutch capability, which prevents slipping, but also allows limited usage as the system engages and disengages. Also, the system checks electric motor speed versus the speed of the engine and wheels to determine whether an engaged clutch is slipping. This clutch slip measurement then degrades the clutch capability used by the supervisory control for mode operation. The low level control combined with the fault monitoring and torque prediction of the supervisory control system provides a robust and reliable clutch actuation operation for vehicle mode transitions.

5.4.2 Engine Starting

The supervisory control is critical to engine starting from an overall management perspective, but also because the FEM is used to perform cranking. The engine start process requires the supervisory control to anticipate engine start by sending a warm up request beginning the engine’s procedure to heat sensors and the electrically heated
catalyst (EHC). Then once complete the engine sends a status, which allows the supervisory control to complete the startup. Figure 47 shows the procedure shared by the supervisory control and engine control to start the engine.

Figure 47: Engine Startup Process

The engine start mode is also responsible for cranking the engine quickly and continuing to crank until the engine start is complete. Therefore, the algorithm commands the start torque of the engine, cranking speed, and remains in crank until the engine controller reports the engine start is complete.

5.4.3 Series/Parallel Transition

The series/parallel transition provides speed matching of the clutch system before engaging the gearbox to the wheels and releases torque from the clutch before disengaging. The speed matching is performed within the transition mode from series to parallel and the release of torque is performed in the same transition mode, but with a flag indicating the transition is from parallel to series. The series/parallel transition ensures the smoothest engagement and disengagement of the clutches possible and completes the transition in only 1-2 seconds, which is triggered by the clutch position.
Figure 48 shows the series to parallel transition speed match, which shows the action taken by the FEM to slow the engine speed to match the transmission input shaft. The vehicle modes in Figure 48 are 3 – series, 4 – parallel, and 5 – transition speed match.

![Figure 48: Clutch Speed Match From Series To Parallel Modes](image)

### 5.5 Software for Supervisory Control Implementation and Deployment

The supervisory control is designed and developed in Matlab/Simulink, which provides the clear object oriented programming required to develop software quickly. The control model is initialized with calibration variables from simple constants to efficiency and consumption maps, which are easily saved in Matlab as well as loaded with a simple script. The control model uses Simulink blocksets designed for the dSPACE MABX, which provides setup, inputs, outputs, and configurations necessary for Simulink models.
to run on the real-time controller. The model uses typical Simulink organization, which
includes subsystems and signal bus structures. In order to implement operational states
quickly and efficiently Stateflow is employed to outline distinct states and variables
needed to structure conditions, rules, and operation effectively. This total model creates
structured, visual, well organized supervisory control software, which is easily updated,
edited, and replaced for development. Lastly, implementation in Simulink also provides
access to place the control model inside a desktop vehicle simulation, which is used to
predict, analyze, and debug the performance of the supervisory software.

Once a software model is created Simulink is compiles to C-code using the included
Real-time Workshop, which then compiles through the dSPACE compiler. This process
automatically completes by loading the compiled software to the target MABX through
dSPACE Controldesk. In vehicle software testing can be monitored by both the
Controldesk software or by monitoring CAN traffic with a tool such as Vector CANape
(which is used by OSU EcoCAR). The Controldesk software allows any parameter found
in the model to be temporarily adjusted for testing and calibration, which can later be
updated and flashed. Figure 49 shows and example Controldesk layout for in vehicle
ingen engine testing. Figure 50 shows a screen in the Vector CANape data logging
configuration for OSU EcoCAR.
Figure 49: dSPACE Controldesk Layout for in Vehicle Engine Testing
5.6 Software Testing and Results

Software testing included three theoretical stages, which after initial development are often shuffled based on need. These stages include, first, using a desktop simulation to verify algorithm functionality, second, using a hardware simulator to validate real-time controller functionality, and finally, using the real vehicle hardware to validate proper operation and simulation results. In further development, only calibration changes are made and validation is done directly on vehicle. The testing results provided extensive revision in algorithms to correct errors and improve designs, which provided the final algorithms described above.
5.6.1 Local on Road Testing

Vehicle testing is ideally done in a controlled environment at first, but must be done on road at some point to confirm robust operation in less predictable circumstances. Vehicle testing included two specified drive cycles on public roads, but also included data recorded for normal vehicle usage. Figure 51 and Figure 52 show the OSU EcoCAR cycle representative of an urban setting and Table 11 shows the cycle statistics. Figure 53 and Figure 54 show the cycle representative of a more aggressive highway schedule and Table 12 shows the cycle statistics.
Figure 51: Urban Drive Cycle Speed Trace

Table 11: Urban Drive Cycle Metrics

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>5.2 miles</td>
</tr>
<tr>
<td>Length</td>
<td>11 minutes</td>
</tr>
<tr>
<td>Max Speed</td>
<td>110 km/h</td>
</tr>
<tr>
<td>Average Acceleration</td>
<td>0.67 m/s²</td>
</tr>
</tbody>
</table>

Figure 52: Urban Drive Cycle Route
Table 12: Highway Drive Cycle Metrics

Distance: 27.3 miles
Length: 33 minutes
Max Speed: 120 km/h
Peak Acceleration: 2.8 m/s²
Average Acceleration: 0.46 m/s²
The local on road testing was able to provide extensive tuning to transitions and driveability, but efficiency was not easily compared due to cycle variation. Figure 55 shows vehicle speed, component torques, and battery SOC over an urban drive cycle and Figure 56 shows the same data over a highway cycle.
Figure 55: Urban Drive Vehicle Test Data
These results in Figure 55 and Figure 56 the types of operation based on speed. The data also shows that charge sustaining operation was forced manually for test purposes in each data set. Table 13 shows the estimated improvements to fuel efficiency progressively over a period of calibration improvements.
Table 13: Highway Fuel Consumption Test Results

<table>
<thead>
<tr>
<th>Test date</th>
<th>Mpg E85</th>
<th>Mpgge</th>
<th>L/100 km E85</th>
<th>L/100km gasoline EQ</th>
<th>Delta SOC</th>
</tr>
</thead>
</table>

5.6.2 Environmental Protection Agency (EPA) and Transportation Research Center (TRC) Dynamometer Testing

Vehicle development testing and tuning required some uniform, repeatable tests, which could not be produced by on road testing. On road testing provided data for overall functionality, driveability, and transitions, but fuel economy and emissions were not well known or measured. In order to provide this repeatable, accurate testing the EcoCAR Competition organized an event at the EPA National Vehicle and Fuel Emissions Laboratory (NVFEL), which offered 4-wheel chassis dynamometers with modal and bagged emissions analysis. For further testing, the team also arranged testing in a facility locally at TRC, which offered further tuning on a 4-wheel chassis dynamometer with bagged emissions analysis. Testing at the EPA and TRC was primarily targeted at engine software and calibration in order to meet emissions, but supervisory controls tuning included the engine start sequence for the Electrically Heated Catalyst (EHC), the Equivalence Factor (EQF) for the ECMS algorithm used on the highway, and the PI control used for series operation to maintain the target battery SOC value. Figure 57 shows the initial FUDS cycle driven at the EPA, then Figure 58 shows the final FUDS driven at TRC.
Figure 57: EPA FUDS Drive Cycle Test Results
Figure 58: TRC FUDS Drive Cycle Test Results

Figure 59 shows the initial FHDS cycle driven at the EPA, then Figure 60 shows the final FHDS driven at TRC.
Figure 59: EPA HWFET Drive Cycle Test Results
Figure 60: TRC HWFET Drive Cycle Test Results

The results shown in Figure 57 - Figure 60 show the overall operation of the vehicle components follow charge sustaining operation during all cycles, which was manually engaged. The final HWFET driven at TRC shows an added hysteresis to charge
sustaining operation as compared with Figure 57, which only shuts down momentarily on three occasions when the battery charge exceeds the charge sustaining region of battery SOC. All cycles show high frequency torque is handled by the FEM, which is capable of responding to combustion pulses of the engine, which is seen during series operation.

5.7 Conclusion
The supervisory control of any hybrid vehicle has a vital role in the overall efficiency, fuel economy, and emissions. The OSU EcoCAR vehicle demonstrated excellent efficiency, excellent emissions, and reliable operation both in testing and as demonstrated at the EcoCAR Competition at the General Motors Milford Proving Grounds. The supervisory control balances driveability, performance, and efficiency in all modes and regardless of whether the energy source is electricity or fuel, which proves success of the control system as well as the selected architecture. Further testing and calibration can provide additional improvements, but as demonstrated in testing significant improvement was achieved with tuning, which allowed the vehicle to meet goals set in the design process. The vehicle architecture and control structure provides many more opportunities for experimentation with additional control algorithms as well in the future, but in the time available a well balanced system was achieved.
INTRODUCTION

Driveability is often a very objective metric or goal. Metrics for driveability are measured with accuracy using accelerometers, microphones, and other devices, but the goals are relative to achievable standards and other vehicles in a competitive market or class. Therefore, overall goals point towards production vehicles on the market today when targeting improvements for the EcoCAR vehicle. These metrics include a variety of shift quality, engine start, linearity of accelerator pedal response, noise, and vibration. Some of these have been measured, while others are discussed in terms of objective improvements.

6.2 Metrics

The metrics used for analysis are similar to those found in literature, but many must be catered to the architecture and extended-range electric vehicle (E-REV) operation. Table 14 shows the considered metrics.
Table 14: OSU EcoCAR Driveability Metrics

<table>
<thead>
<tr>
<th>Metric</th>
<th>Description</th>
<th>Measurement Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Start Time</td>
<td>Time from initiating crank to obtaining desired output torque</td>
<td>CAN feedback from control system</td>
</tr>
<tr>
<td>Powertrain Vibration and Rattles</td>
<td>Vibration and rattles caused by rough powertrain operation such as rough engine idle</td>
<td>Objective observation</td>
</tr>
<tr>
<td>Overall Smoothness of Vehicle Operation</td>
<td>Oscillations during driving, delivery of torque to wheels in terms of consistency, gear backlash, etc.</td>
<td>Objective observation, Accelerometer, CAN feedback from control system</td>
</tr>
<tr>
<td>Shift or Transition Quality</td>
<td>Jerk or smoothness of clutch engagement from series to parallel</td>
<td>Accelerometer and objective observation</td>
</tr>
<tr>
<td>Accelerator Pedal Linearity</td>
<td>Accuracy of control system at mapping accelerator command to percentage of torque</td>
<td>Objective observation and accelerometer</td>
</tr>
</tbody>
</table>

6.3 Improvements to Control System

The control system software and design structure is capable of overcoming many of the issues with driveability easily, but requires a proper understanding of causes and a solution to address them. Software structure and communication play a vital role in driveability, but also calibration results in significant improvements.

6.3.1 Delay

Delay or lag can manifest as many driveability issues. The most obvious is a poor response to driver inputs, but is easily recognized and improved with tuning or software modifications. The first and most direct links to delay or lag in pedal response is caused by filters and rate limits applied to output signals of speed or torque commands. The rate limits and filters reduce the time constant or response of the vehicle’s powertrain systems to the driver by forcing the system input from the control to follow the filtered or rate limited trajectory. Therefore, filters in the OSU EcoCAR system are used sparingly and
never where driver requests are influenced. Filters are instead applied to signals such as speed that might cause disturbances in the control system operation. Next, rate limits are placed on all powertrain components, but calibrated to rates well beyond driver recognition and near systems maximum response time. Rate limits serve to protect against harmful errors in commands and not improve driveability.

Rate limits and a filter are encountered in the torque request to the engine, which is remedied with the FEM providing the difference between the raw request and the limited and filtered request. This solution helps to remove transients from the engine and still realize torque transients, which may even occur faster given the FEM has a faster time constant than the engine. Rate limits and filters are also used in control signals for powertrain operation that does not deliver the driver torque request. This operation is primarily the speed request of the FEM during engine start, clutch transitions, and series operation. In these three cases, the FEM operates in speed mode to deliver a requested speed independent of the drive torque, therefore, rate limits serve to regulate safe and reliable operation. However, these rate limits must be calibrated to not interfere with the clutch engagement time and the engine start performance. The comparison of different rate limits used for the clutch speed matching are shown in Figure 61 and Figure 62, which show the engine and FEM speed during a transition and the zeroed accelerometer reading respectively. The figures show that a faster rate limit is desirable in order for the speed match to be complete before torque is transmitted through the clutch to the wheels. If the rate limit is too slow a harsh transition occurs due to inertia of the engine and FEM being transferred to the wheels, however, a rate limit excessively high could cause the
FEM or shafts and components performing the speed match to absorb too much inertia and fatigue or fail. The rate limit demonstrated balances these two trade-offs to provide a smooth transition.
Figure 61: Comparison of Speed Matching for Clutch Engagement
An additional result shown from rate limit adjustment is an oscillation, which causes noise and vibration when the cranking rate limit is too low. The initial rate limit for FEM speed change during cranking caused engine compression pulses to far exceed inertia of the flywheel, which can be seen as FEM torque oscillations as the machine tracks a speed trajectory. The torque of the FEM during cranking for two rate limits is shown in Error! Reference source not found. and the FEM speed during cranking for the same two rate limits is shown in Error! Reference source not found.. The original slow rate limit for speed causes large oscillations in torque for a sustained time period as compared to the faster rate limit allowing the system to achieve higher speeds quickly and gain the needed inertia for smooth operation.
Figure 63: FEM Torque during Cranking for Two Different Rate Limits

Figure 64: FEM Speed during Cranking for Two Different Rate Limits
6.3.2 Hysteresis

The use of hysteresis in control systems serves to handle small oscillations, primarily, found in real-time where signals include small amounts of noise, which are best filtered out or ignored. The hysteresis creates a band in which the system can be in either condition depending on whether it is decreasing or increasing. The hysteresis used on the EcoCAR vehicle is seen in two distinct operations, but an additional form is discussed in the section on ECMS. The first operation is the clutch engagement, which transitions from series to parallel or back. In this mode change, the hysteresis is added to the speed threshold at which the transition takes place. The hysteresis eliminates oscillations and shifts seen when crossing the speed threshold or especially when maintaining a speed near the threshold. Figure 65 shows the clutch position and vehicle mode during a transition from series to parallel with and without hysteresis. The transition shows that without hysteresis a transition both out and back into the parallel mode occurs, but with the addition of hysteresis around the speed threshold the transition occurs only once without oscillation. The hysteresis eliminates the transition oscillations and ensures only one shift, which drastically improves driveability during the transition or around the speed threshold.
Figure 65: Clutch Position and Vehicle Mode Before and After Adding Hysteresis to the Control Threshold

An additional hysteresis was added around the battery SOC threshold triggering a transition from all electric charge depleting operation to charge sustaining operation. This helped to reduce the frequency of transitioning back to charge depleting operation.
should the vehicle be driven in a manner allowing the system to charge the battery. Instead the system allows a buffer where the vehicle can charge slightly without changing modes as well as remain charge depleting until reaching the target battery SOC value to be sustaining. This result is seen in Figure 57 and Figure 60, which shows that in the first cycle before adding hysteresis to the battery threshold a transition was made three times due to operating near the threshold, but in the later cycle hysteresis brings the battery charge completely down to the target value and again begins to charge sustain.

6.3.3 ECMS Driveability
The ECMS algorithm requires optimization and revision in order to address driveability issues as the ECMS algorithm only considers efficiency and leaves little adjustment for driveability. However, identifying the different regions of operation where ECMS presents driveability concerns shows a few different solutions to improve driveability. These areas of concern include resolution, oscillations, and torque jumps. These driveability issues can be addressed with small changes to calibration and mapping, but also require small modifications or additions to the algorithm.

6.3.3.1 Algorithm Order
In theory, the ECMS algorithm would operate the same regardless of the order in which computations are made, however, the modifications made to operate in real-time cause the algorithm to produce different results based on the order of certain computations. The change is briefly described in the previous chapter for the ECMS algorithm. The different possible combinations of torques from each component are combined and used
to find the operating point with the global minimum fuel consumption. In real-time these different operating points must be formed as a discrete matrix of points, which creates a need for interpolation or modification to meet the exact driver requested torque instead of the nearest possible operation point. In order to select from discrete points, which meet the driver’s request exactly one component completes the sum of all components, which exactly meets the driver request. In this way, there are two components with discrete points chosen based on possible operation at that speed, but the last component varies in order to make up the difference and then this component’s limits are used to throw out impossible combinations. By changing this last component that takes variable operation to meet the driver’s request, transient operation can be moved from one component to another. Original algorithms for ECMS put the engine as the variable or transient component, but for many reasons including driveability the FEM was switched with the engine. This change in algorithm order smoothed engine operation and created better driveability in terms of noise, response time, and oscillations. Figure 66 shows a comparison of the change in algorithm order as shown with simulation data and Figure 67 shows a comparison of the change in order with vehicle data. The plotted comparisons demonstrate that algorithm order for this type of computation offers a drastic improvement in smooth engine operation, which helps to improve the overall vehicle driveability, but also benefits fuel efficiency and emissions as shown previously in Figure 42 and Figure 43.
Figure 66: ICE Torque Comparison for ECMS change in Algorithm Order (Simulation)
6.3.3.2 Resolution

The discrete points used in ECMS to search for the minimum fuel consumption can be improved in multiple ways. The resolution results must first be benchmarked. Therefore, the control system is run for both a 21 x 21 point grid and a 200 x 200 point grid, which offers the current real-time resolution results next to the nearly best possible results.

Secondly, a system which provides the similar resolution quality using a 21 point search is developed. Table 15 shows a comparison of the fuel economy and final SOC on the FHDS. All simulation and testing is done with a target SOC of 30 percent. The tabulated results confirm the three different variations are very similar in efficiency, but trade fuel economy for SOC or SOC for fuel economy.
Table 15: Search Resolution Comparison

<table>
<thead>
<tr>
<th>Grid Size</th>
<th>E85 fuel economy (mpg)</th>
<th>Final SOC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 x 200</td>
<td>19.86</td>
<td>30.39</td>
</tr>
<tr>
<td>21 x 21</td>
<td>20.05</td>
<td>29.02</td>
</tr>
<tr>
<td>Variable limit 21 x 21</td>
<td>19.80</td>
<td>30.46</td>
</tr>
</tbody>
</table>

Using these three sets of results the torque commands are compared. The potential for drivability issues and oscillations are present in all three systems, but most pronounced is the magnitude of oscillations in the original 21 point grid, which intuitively shows that improvements in resolution can also improve drivability. **Error! Reference source not found.** - Error! Reference source not found. show the three grid sizes by comparing the FEM, REM, and ICE torque respectively.

![FEM Torque](image)

Figure 68: Grid Comparison for FEM Torque with Simulated ECMS operation for FHDS
Figure 69: Grid Comparison for REM Torque with Simulated ECMS operation for FHDS
6.3.3.3 Torque Oscillations

The ECMS algorithm is very susceptible to torque oscillations in components torque commands, however, proper tuning and algorithm design can prevent oscillations, which harm driveability. The ECMS algorithm searches globally for the operating point with the minimum fuel consumption; therefore, finding a minimum at a point with drastically different component torques is possible. There are two methods, in which, a needless jump in torque can be prevented for the purpose of efficiency. The first method is to ensure power and fuel consumption maps are smooth without distinct peaks and valleys created from measurement error or inaccuracies. The second method is to add a
hysteresis for the search function where the optimum must provide a significant improvement before a change in operation occurs.

For the first method, smoothing power and fuel consumption maps, the Mathworks Model Based Calibration (MBC) Toolbox for Matlab was used. This tool takes test data collected for the given electric machine or engine and fits a precise model to the data using the given inputs. For electric machines the inputs are speed and torque with an output of electric power. By fitting a model a high resolution map can be created with a uniform grid, which is not possible with the test data due to variations in measurements and test conditions. This fitted model also helps to smooth peaks and valleys, which are often caused by rounding errors or small inaccuracies in measurement. Figure 71 and Figure 72 show the first power map before fitting a model and the second after obtaining data from a fitted model. The two maps have no difference in overall trends, but the model based map provides accurate boundary data for all regions of the map as well as smoother contours can be seen primarily in boundary areas where test data is sparser.
Figure 71: Electric Machine Power Map Before Model Fitting
The last method to improve ECMS driveability is an algorithm efficiency hysteresis. This is best described as a stability reward assigning an increased efficiency to remaining at the same operating point. In this way the algorithm can still function to find the best efficiency, but small changes in efficiency will not cause the system to oscillate between operating points. Simulating the vehicle driving the Federal Highway Driving Schedule (FHDS) Table 16 shows the comparison of the original ECMS strategy and the ECMS strategy using a stability reward.

Figure 72: Electric Machine Power Map After Model Fitting
Table 16: ECMS with and without Stability Reward Comparison

<table>
<thead>
<tr>
<th>ECMS version</th>
<th>E85 fuel economy</th>
<th>Final SOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard ECMS</td>
<td>21.29 mpg</td>
<td>28.67 %</td>
</tr>
<tr>
<td>ECMS with Stability Reward</td>
<td>21.24 mpg</td>
<td>28.68 %</td>
</tr>
</tbody>
</table>

Error! Reference source not found. and Error! Reference source not found. show a problem region of the commanded torque for both REM and FEM during the simulation of the FHDS. The figures compare this region of operation for the original ECMS algorithm and one using a stability reward. In the stability reward algorithm, the efficiency is artificially increased by 2% for any operation that remains at the same point as the previous computation of the ECMS algorithm. This value was chosen based on observing results for a simulation of the FHDS using a reward value of 0.5%, 1%, and 2%, and 3% which showed best improvements at 2% with virtually no change in fuel consumption. In order to quantify the overall improvement in high frequency switching, the RMS of the derivative for the torque command of the REM and FEM is computed for the entire FHDS simulation. The comparison of the RMS derivative is done by computing the average for the original ECMS results and the reward function ECMS results. Table 17 shows the comparison of the RMS of the torque derivative, which shows a decrease in the average RMS derivative when using a reward function. The lower average RMS derivative torques show the system remains steady more than the typical ECMS algorithm, which is seen by the drop in the average RMS derivative.
Table 17: Comparison of Average RMS Derivative Torque

<table>
<thead>
<tr>
<th>Component</th>
<th>REM</th>
<th>FEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original ECMS Average RMS Derivative Torque [Nm/s]</td>
<td>0.318</td>
<td>0.784</td>
</tr>
<tr>
<td>Reward Function ECMS Average RMS Derivative Torque [Nm/s]</td>
<td>0.284</td>
<td>0.689</td>
</tr>
<tr>
<td>Percent Improvement</td>
<td>10.7%</td>
<td>12.1%</td>
</tr>
</tbody>
</table>

Figure 73: High Frequency Oscillation Event for REM During Simulation of FHDS
The same effect of the efficiency hysteresis implemented in ECMS can be seen when driving two identical cycles on a chassis dynamometer. In this stationary setting, the REM torque command still reveals the effects of the hysteresis on maintaining a command with significantly less oscillations. With the lower number of oscillations, driveability improves due to less driveline dynamics and no need for a change in commands to be realized. The cycles driven are both overlaid based on speed for the FHDS test and shows a near exact match in driven speed, but with a large number of oscillations in the algorithm using no hysteresis. Figure 75 shows the vehicle speed on the chassis dynamometer and the REM torque commanded by ECMS with and without a hysteresis.
Figure 75: Test Results from EPA Dynamometer Comparison of ECMS

6.4 Conclusion

Vehicle driveability is a complex goal to achieve, but with access to many controls features and component commands, solutions can be designed and calibrated that provide excellent balance between driveability and efficiency. Excellent driveability can also provide a more luxurious feel and comfort to a vehicle, but may also reduce wear and tear on components by reducing vibration and harshness. In the current vehicle market driveability is extremely important to controls by consumer demand for both quality and performance. The algorithms and calibration for the OSU EcoCAR vehicle provided many solutions and excellent improvements to a basic vehicle control system, but certain
areas would need further refinement in hardware or software to meet or exceed some consumer markets.
CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7.1 Conclusions
The OSU EcoCAR Team and vehicle proved very successful in all aspects. The team was well organized at meeting deadlines, goals, and commitments, which required dedication and lots of teamwork. The vehicle was one of the most aggressive designs conceived in an advanced vehicle competition series. The vehicle had a large amount of custom designed components and systems as well as a very unique approach to meeting performance targets and goals. The system provided a wealth of learning and training experiences for students, but also presented challenges and excitement in the intense design, construction, and refinement of the vehicle.

7.1.1 Overall Team Results
The team structure and involvement changed significantly from the Challenge X competition that preceded as well as during the three years of the EcoCAR competition. The team membership increased to roughly double the size previously maintained on the team, which was largely due to interest and a wide variety of challenging and exciting projects. The team also gained a significant number of young students early in the first and second year of EcoCAR, which helped to provide continuity and long term team
members. Many of these students became leaders on the team during the second and third year helping to expand the leadership and management of the team to new students. In addition to engineering students, the EcoCAR team continued the business and outreach team emphasis to promote education and community outreach. This outreach team was formed in the Challenge X competition and evolved with EcoCAR, which included grants and student funding to support the outreach team. The outreach team maintained very high placement in scoring and judging throughout EcoCAR. The overall team placed first, fifth, and second throughout the three years of the EcoCAR competition respectively. This record reflects the team’s success, hard work, and dedication, which is only discounted by a fifth place finish in the second year due to timelines far too aggressive for completion.

7.1.2 Overall Vehicle Results
The final vehicle produced for the EcoCAR competition met or exceeded nearly all goals. The vehicle drastically reduced fuel consumption and improved performance. In addition, the vehicle demonstrated outstanding reliability and functionality. The vehicle produced nearly seamless transitions and operation and demonstrated the architecture could deliver outstanding driveability and efficiency. The final vehicle measured results are shown compared to the original goals in Table 18.
Table 18: Vehicle Technical Specifications Goals Compared to Final Results

<table>
<thead>
<tr>
<th>Specification</th>
<th>Predicted OSU E-REV</th>
<th>Actual OSU E-REV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration 0-60 (s)</td>
<td>9.9 s</td>
<td>10 s</td>
</tr>
<tr>
<td>Acceleration 50-70 (s)</td>
<td>5.0 s</td>
<td>5.8 s</td>
</tr>
<tr>
<td>Towing Capacity (kg, (lb))</td>
<td>1,130 kg @ 3.5%, 20 min @ 72 kph (45 mph)</td>
<td>≥ 680 kg @ 3.5%, 20 min @ 72 kph (45 mph)</td>
</tr>
<tr>
<td>Cargo Capacity (mm, (in))</td>
<td>Height: 730 mm (28.7&quot;) Depth: 800 mm (31.5&quot;) Width: 900 mm (35.4&quot;)</td>
<td>Height: 730 mm (28.7&quot;) Depth: 800 mm (31.5&quot;) Width: 900 mm (35.4&quot;)</td>
</tr>
<tr>
<td>Passenger Capacity</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Braking 60-0 (m, (ft))</td>
<td>42 m (138 ft)</td>
<td>37 m (121.5 ft)</td>
</tr>
<tr>
<td>Mass (kg, (lb))</td>
<td>2,109 kg (4,650 lb)</td>
<td>2,199 kg (4,849 lb)</td>
</tr>
<tr>
<td>Starting Time (s)</td>
<td>&lt; 5 s</td>
<td>4 s</td>
</tr>
<tr>
<td>Ground Clearance (mm, (in))</td>
<td>168 mm (6.6 in)</td>
<td>165 mm (6.5 in)</td>
</tr>
<tr>
<td>Range (km, (mi))</td>
<td>418 km (260 mi)</td>
<td>399 km (248 mi)</td>
</tr>
<tr>
<td>Fuel Consumption, CAFÉ Unadjusted, Combined, Team: UF Weighted (l/100km)</td>
<td>3.4 l/100km (69.2 mpgge)</td>
<td>3.2 l/100km (73.5 mpgge)</td>
</tr>
<tr>
<td>Charge Depleting Fuel Consumption (l/100km)</td>
<td>0 l/100km (ge)</td>
<td>0 l/100km (ge)</td>
</tr>
<tr>
<td>Charge Sustaining Fuel Consumption (l/100km)</td>
<td>8.8 l/100km(ge)</td>
<td>8.5 l/100km(ge)</td>
</tr>
<tr>
<td>Charge Depleting Range (km, (mi))</td>
<td>64.4 km (40 mi)</td>
<td>65.7 km (40.8 mi)</td>
</tr>
<tr>
<td>Petroleum Usage (kWh/km)</td>
<td>0.10 kWh/km</td>
<td>0.08 kWh/km</td>
</tr>
<tr>
<td>Emissions</td>
<td>&lt; Tier II Bin 5</td>
<td>&lt; Tier II Bin 3</td>
</tr>
<tr>
<td>WTW GHG Emissions (g/km)</td>
<td>210 g/km</td>
<td>190 g/km</td>
</tr>
</tbody>
</table>

Besides meeting or exceeding goals set when designing the EcoCAR vehicle the architecture offers an enormous amount of versatility for future research and work, which can be done with different components connected to the system as well as different mixtures of electric and engine operation. These combinations all offer many opportunities to test theory and experiment with vehicle hardware. The EcoCAR vehicle
was an outstanding success and will provide an excellent educational value even beyond the educational experience given during construction and testing during competition.

7.2 Future Work

As previously stated the EcoCAR vehicle architecture provides a versatile system for many tests on sensitivity to different aspects of the system or control. Therefore, the software testing could continue with many additional tests and improvements to calibration and software. The vehicle, additionally, would benefit from hardware improvements. These improvements could improve efficiency, performance, and reliability with strengthened, lighter, or more modern components.

7.2.1 Further Software Improvements

There are four primary areas for controls improvement based on research and experience that could be further investigated. The first is the transition threshold for speed and battery SOC are both based on success in testing at these points and not based on optimal performance as found in a simulation study of a wide variety of thresholds or a wide variety of tests for different thresholds. The speed threshold being lowered could provide parallel operation sooner and therefore the efficiency benefit it offers. The battery SOC threshold for changing from charge depleting to charge sustaining drastically changes the utility factor weighting by changing the electric range, but this would need compared to the decrease in battery efficiency as well as the impact on battery life. The current thresholds provide excellent results, but lowering or increasing the thresholds could potentially improve driveability, efficiency, and reliability. The second area of
improvement is related to electric machine calibration and test data, which can also be solved with a hardware improvement as discussed in the next section. The EV1 used for the REM did not have a comprehensive set of test data matching the inverter control, which required adaptation of known test data as well as in vehicle testing. Therefore, a thorough mapping of power along with inverter tuning in a stationary dynamometer test stand could provide significant improvement to the electric machine operation. More accurate test data would offer a more precise match between commands and actual output, which would improve operation for pedal response as well ECMS operation where the torque must match very precisely to prevent oscillations. A third controls improvement would involve software and calibration for regenerative braking, which would consider stability in various surface conditions. The software would change the object of the regenerative braking from being based on efficiency to also consider the most stable operation possible to prevent wheel slip during braking, which would ensure regenerative braking always remains safe. The fourth and final area for controls testing and improvement could be found with investigation of additional control algorithms. The primary algorithms to consider would be a substitution of a neural network in place of ECMS, which could be trained for both driveability and efficiency. The results of simulation or algorithm development could reveal an artificial neural network can deliver better overall performance when correctly trained.

### 7.2.2 Further Hardware Improvements

There are two primary areas in which the vehicle hardware would benefit from improvements. The primary component or concern is the GM EV1, which is the rear
electric machine in the vehicle. This component offers high power density and torque, but lacks modern controls and efficiency both in the machine as well as the inverter and power electronics. During the third year of EcoCAR investigation and work was done to design a replacement system using the Phoenix International FI-9 inverter and Remy HVH250 used for the FEM. This system or another of similar power and efficiency with a better interface to controls (CAN) would drastically improve series efficiency, all electric efficiency, ECMS operation, and reliability. In the current EV1 system, there is very little access to accurate feedback and precise control signals, which in a new system would improve the control and operation. There would also be better access to accurate test data with actual operation more closely matching that of the inputs, which was not always true in the analog control used for the EV1.

The second hardware upgrade that would potentially improve operation of the vehicle is a higher torque clutch system. In the current system, software limits prevent clutch slip as well as detection software, however, this decreases the capable performance of the vehicle given the electric machine could deliver roughly 38 percent more torque if the clutch could permit the added load. This additional clutch torque could also provide additional regions of operation for the ECMS algorithm, which might allow improvements to the overall efficiency and driveability.

7.2.3 Control Access for Improvement

The final improvement that could be made to the EcoCAR vehicle or further investigated is the hybrid brake system for blending friction brakes with regenerative braking. The system in place on the vehicle would allow regenerative braking to completely replace
the friction braking until saturated, at which time, the friction system would be blended with regenerative braking. The electronic braking system has control to remove or deliver brake pressure with the driver pedal feel being emulated for the given amount of brake torque. However, due to safety concerns for the vehicle development and reliability the software was modified to lock the blending of regenerative braking out, which instead forces the system to operate as a traditional boosted friction brake system. This modified software forces all regenerative braking to be additive, which limits the recovered energy of regenerative braking. Therefore, restoring the original brake software would allow the increased regenerative braking capability to recover larger amounts of braking energy to further boost vehicle efficiency.
BIBLIOGRAPHY


APPENDIX A: DESIGN ANALYSIS DOCUMENT

9.1 Belt Drive Analysis

![Belt Drive Analysis Diagram]

**Belt**
- Belt part number: P-1120
- Belt speed: 9449 ft/min; 0.254 kg/m
- Belt power rating: 209.8 Hp

**Pulley**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00</td>
<td>0.00</td>
<td>48</td>
<td>4.81</td>
<td>/</td>
<td>7500.0</td>
<td>3.35</td>
<td>14.5</td>
</tr>
<tr>
<td>1</td>
<td>12.54</td>
<td>0.00</td>
<td>72</td>
<td>7.22</td>
<td>/</td>
<td>5000.0</td>
<td>3.35</td>
<td>22.9</td>
</tr>
</tbody>
</table>

**Pulley Sprocket part number & bushing**
- 0: P-48S-MPE
- 1: P-72S-MPE

**Absorbed power [Hz]**
- 0: 90.0
- 1: 90.0

**Required service factor**: N/A

**Side**: Inside

**Type**: Fixed

**Hub loads & tensioning**

<table>
<thead>
<tr>
<th>Span</th>
<th>Dynamic hub load (used) [lbs]</th>
<th>Static hub load (now; used) [lbs]</th>
<th>Deflection force [lb]</th>
<th>Deflection [inch]</th>
<th>Span length [inch]</th>
<th>Frequency (now; used) [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>367.4</td>
<td>87.2 ; 628.0</td>
<td>30.8 ; 22.9</td>
<td>0.20</td>
<td>12.48</td>
<td>138.7 ; 117.2</td>
</tr>
<tr>
<td>1</td>
<td>367.4</td>
<td>87.2 ; 628.0</td>
<td>30.8 ; 22.9</td>
<td>0.20</td>
<td>12.48</td>
<td>138.7 ; 117.2</td>
</tr>
</tbody>
</table>

**Installation strand tension**
- Installation strand tension (new, used): 441.6 lbs
- 315.5 lbs

**Comments**
- Recommended center distance movement for installation and take up: 0.40 inch to 0.12 inch
- Check shaft lengths!
- Ensure Drive and Driven bearings can handle hub load.
- Drive must be properly aligned to give intended service life!
- Noise levels over 85(dB(A)), may need noise protection for personnel!
- Special material balancing is required due to high belt speed! Please contact your sprocket/pulley supplier or Veyance technical representative.
# APPENDIX B: NOMENCLATURE

Table 19: Nomenclature Definitions

<table>
<thead>
<tr>
<th>Abbr.</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>VTS</td>
<td>Vehicle Technical Specifications</td>
</tr>
<tr>
<td>E-REV</td>
<td>Extended-Range Electric Vehicle</td>
</tr>
<tr>
<td>ICE</td>
<td>Internal Combustion Engine</td>
</tr>
<tr>
<td>FEM</td>
<td>Front Electric Machine</td>
</tr>
<tr>
<td>EHC</td>
<td>Electrically-Heated Catalyst</td>
</tr>
<tr>
<td>REM</td>
<td>Rear Electric Machine</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer-Aided Design</td>
</tr>
<tr>
<td>GREET</td>
<td>Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation</td>
</tr>
<tr>
<td>PHEV</td>
<td>Plug-In Hybrid Electric Vehicle</td>
</tr>
<tr>
<td>WTW GHG</td>
<td>Well-to-Wheel Greenhouse Gas Emissions</td>
</tr>
<tr>
<td>MIS</td>
<td>Manual Isolation Switch</td>
</tr>
<tr>
<td>EDS</td>
<td>Emergency Disconnect Switch</td>
</tr>
<tr>
<td>A/C</td>
<td>Air Conditioning</td>
</tr>
<tr>
<td>CAN</td>
<td>Controller Area Network</td>
</tr>
<tr>
<td>GCM</td>
<td>General Control Module</td>
</tr>
<tr>
<td>SOC</td>
<td>Battery State of Charge</td>
</tr>
<tr>
<td>ECMS</td>
<td>Equivalent Consumption Minimization Strategy</td>
</tr>
<tr>
<td>ECU</td>
<td>Engine Control Unit</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional-Integral</td>
</tr>
<tr>
<td>DoE</td>
<td>Design of Experiments</td>
</tr>
<tr>
<td>HIL</td>
<td>Hardware in the Loop</td>
</tr>
<tr>
<td>SIL</td>
<td>Software in the Loop</td>
</tr>
<tr>
<td>MBC</td>
<td>Model-Based Calibration</td>
</tr>
<tr>
<td>FCE</td>
<td>Fuel Conversion Efficiency</td>
</tr>
<tr>
<td>UDDS</td>
<td>Urban Dynamometer Drive Schedule</td>
</tr>
<tr>
<td>FUDS</td>
<td>Federal Urban Drive Schedule</td>
</tr>
<tr>
<td>FHDS</td>
<td>Federal Highway Drive Schedule</td>
</tr>
<tr>
<td>HWFET</td>
<td>Highway Fuel Economy Test</td>
</tr>
<tr>
<td>FTP</td>
<td>Federal Test Procedure</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
</tr>
</tbody>
</table>