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Mississippi State University EcoCAR Extended Range Electric Vehicle Thermal System Design, Integration, Optimization, and Validation

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Mississippi State University EcoCAR extended range electric vehicle thermal system design, integration, optimization, and validation

By

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Mississippi State University EcoCAR extended range electric vehicle thermal system design, integration, optimization, and validation

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A continued increase in government regulations for fuel economy and emissions has driven automakers and suppliers to take a large interest in hybridizing vehicles to help them achieve the new requirements. This increased vehicle electrification has resulted in unconventional vehicle cooling requirements. Electrified vehicle batteries and motors operate under different temperature regimes and cooling loads change drastically with driving styles and conditions. A variable-load cooling system was designed, implemented and tested on the Mississippi State University EcoCAR extended-range electric vehicle (E-REV). This system, utilizing variable flow pumps and variable speed fans, was shown to successfully cool the electronic components under the worst-case design conditions, while providing low energy consumption under normal conditions. When compared to a baseline system utilizing no variable duty cycle components, the variable cooling power system reduced energy consumption during testing both on-road at MSU's facility and on-road at General Motors proving grounds in Michigan.

DEDICATION

I would like to dedicate this thesis to my family. Without their support and encouragement none of this would have been possible. Your patience through all of those years is greatly appreciated. Thanks you for everything!

ACKNOWLEDGEMENTS

I would like to acknowledge Mississippi State University for allowing me the opportunity to participate in the EcoCAR competition. I would also like to acknowledge the EcoCAR competition organizers and sponsors for their generosity and dedication to a project that provides a great learning opportunity for students. Finally, I would like to acknowledge and thank Dr. Marshall Molen for his dedication and encouragement to myself and all the students on the Mississippi State University EcoCAR team. Without him the entire project would not have been possible.

TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

LIST OF FIGURES

LIST OF TERMS

A123	A123 Systems, Inc
A/C	Air conditioning
AC	Alternating current
AWD	All wheel drive
CAFÉ	Corporate average fuel economy
CAN	Controller area network
DC	Direct current
E&EC	Emissions and fuel economy
E-REV	Extended range electric vehicle
EV	Electric vehicle
FEAD	Front end accessory drive
FM	Front motor
GM	General Motors
GVDP	Global vehicle development process
HV	High voltage
I	Current
MPPGE	Mile per gallon gasoline equivalent
MSU	Mississippi State University

P	Power
PWM	Pulse width modulation
$\dot{Q}$	Heat generated by battery
R	Resistance
RM	Rear motor
U.S.	United States
V	Voltage

CHAPTER I

INTRODUCTION

Over the last 20 years, oil prices globally have continuously risen, more than tripling in price. Unless the United States reduces its dependence on foreign oil, prices will continue to increase in the coming years [1]. The United States uses more than 6 billion barrels of crude oil every year, while domestic production only accounts for 33% of this demand. As a result, the United States imports over 4 billion barrels of crude oil each year [2, 3]. This dependence on foreign resources introduces uncertainty into the market and allows pricing to be driven by political and environmental events outside of US control. The transportation industry makes up 71% of the petroleum consumed in the U.S. [2]. Additionally, dependence on foreign oil is a growing concern because current estimates show that the U.S. accounts for only 1.7% of the world oil reserves [4]. If the U.S. does not dramatically decrease oil consumption, oil dependence and prices are going to continue to rise.

In an effort to reduce the foreign dependence on oil, government requirements and industry standards related to fuel economy and emissions are becoming more stringent. In 1975 Congress first enacted the Corporate Average Fuel Economy (CAFE) standards, which were meant to increase the fuel economy on vehicles (passenger cars and light trucks) built and sold in the U.S. [5]. The 2012 requirements mandate an average manufacturer fuel economy of 29.7 mpg, increasing to 35.5 mpg by 2016 [6].

New requirements passed into law in 2012 will require the CAFE to be 54.5 mpg by 2025 [7]. In order to meet this mandate, automakers are turning to increased electrification across their vehicle lineups. This study describes a variable-load cooling system developed over three years to improve efficiency on the Mississippi State University EcoCAR extended-range electric vehicle.

1.1 EcoCAR Development

EcoCAR: The NeXt Challenge was a three-year collegiate student engineering competition headline-sponsored by General Motors and the Department of Energy that focused on vehicle design and integration of advanced propulsion technologies. The competition challenged 17 universities across North America to develop a vehicle that minimized energy consumption and reduced greenhouse gas emissions, while retaining the vehicle's performance and consumer appeal. The competition teams followed the General Motors (GM) Global Vehicle Development Process (GVDP) to integrate their advanced technology solutions into a stock production 2009 Saturn VUE crossover vehicle. The first year of the competition emphasized design, modeling, and simulation. The following year focused on creating an operable vehicle by focusing on implementation of the design into the vehicle. The final year of the competition focused on refinement of the vehicle to a near production ready stage.

1.1.1 Vehicle Architecture

The Mississippi State University EcoCAR is a Plug-in Extended-Range Electric Vehicle (E-REV). The vehicle has all-wheel drive (AWD) capability with an all-electric drivetrain giving the vehicle tractive power. A Lithium Iron Phosphate battery pack powers the vehicle making it capable of all electric operation. An E-REV allows the user to drive without using any fuel if driven less than the vehicle's all electric range. After the battery is depleted, a diesel engine that acts as a generator recharges the batteries, giving the vehicle its extended range capability.

1.1.2 Vehicle Specifications

The MSU EcoCAR was designed and built with three major factors taken into consideration: fuel economy, emissions, and consumer acceptability. The ultimate goal of the competition was to make a vehicle that is 99% buyoff ready. A 99% buyoff ready vehicle is essentially ready for production. Every decision that was made during the design and building phases took the concept of 99% buyoff into consideration. The vehicle performed well during both competitions, but due to a component failure at competition year three the fuel economy and emissions results were better at year two competition. A summary of the primary vehicle specifications can be seen in Table 1.1 below.

Table 1.1 Vehicle specifications for the MSU EcoCAR

EcoCAR Specifications	**Competition Required**	**Year 2 Results**	**Year 3 Results**
Acceleration 0-60	≤14 s	12.44 s	5.67 s
Acceleration 50-70	≤10 s	5.23 s	2.83 s
Braking 60-0	< 51.8 m	N/A	43.3 m
Cargo Capacity	N/A	0.83 m^3	0.83 m^3
Passenger Capacity	≥4	5	5
Mass	≤ 2268 kg	2051 kg	2147 kg
Starting Time	≤ 15 s	≤ 2 s	≤ 2 s
Fuel Economy	7.4 l/100 km	1.99 l/100 km	4.34 l/100 km
Petroleum Use	0.65 kWh/km	0.152 kWh/km	0.349 kWh/km
Emissions	Tier II Bin 5	Tier II Bin 7	Tier II Bin 10
WTW GHG Emissions	217 g/km	150 g/km	248 g/km
All Electric Range	N/A	98 km	66 km

1.1.3 Powertrain

The MSU EcoCAR powertrain is comprised of several different components located in all areas of the vehicle. A 125 kW brushless DC motor coupled to a single speed transaxle provides tractive power to the front wheels. The 1.3 L diesel engine coupled to a 75 kW brushless DC motor is also in the front of the vehicle. This engine and generator combination provides supplementary power to the vehicle once the battery is depleted. The rear drive motor is a 145 kW brushless DC motor coupled to a gearbox. Also in the rear of the vehicle is the 21.3 kW-hr Lithium Iron Phosphate high voltage battery pack. The location of the components in the vehicle can be seen in Figure 1.1.

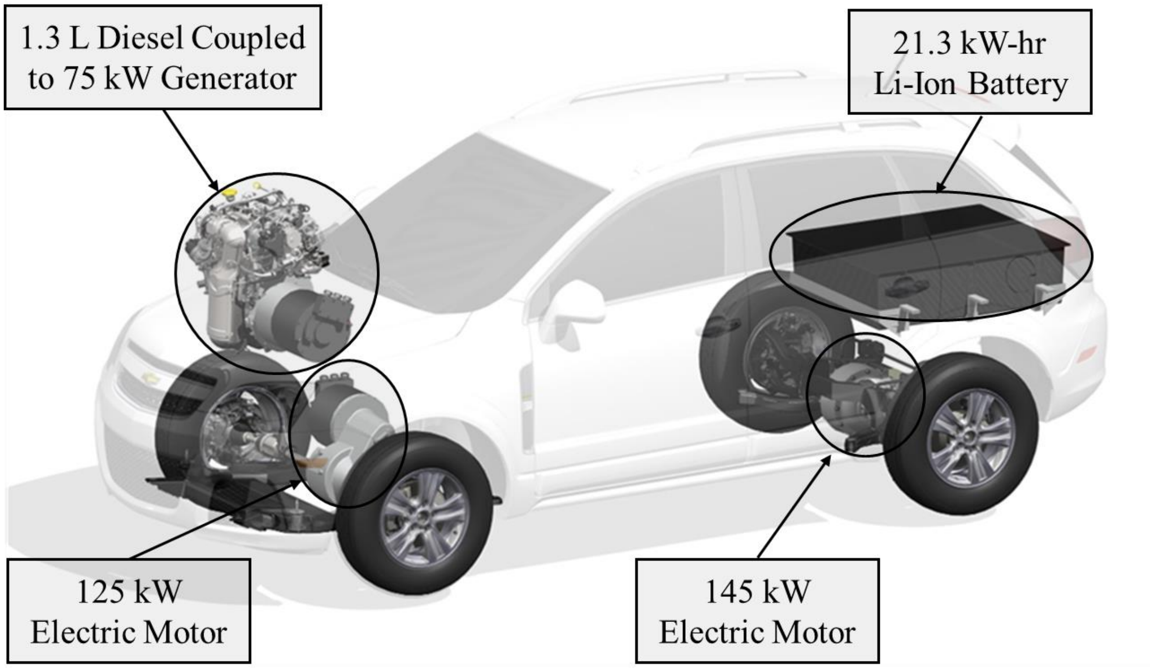

Figure 1.1 Powertrain component layout.

All of the above components that make up the powertrain are liquid cooled. It is important for the thermal system to be an effective use of energy and space. All of the components produce and consume a large amount of power, and therefore produce a large amount of heat. To have a reliable and competitive vehicle, a thermal system that is efficient and effective is critical. Liquid cooling is necessary to extract the large amount of heat produced by the components.

1.2 Electrified Vehicle Development Challenges

The difficulties behind developing an E-REV can include packaging, cooling, controls, and complexity. Packaging all of the required components can often be a difficult development task because an E-REV requires additional components not found in a conventional vehicle. The control systems take a significant amount of engineering to make the new systems on the vehicle work in conjunction with one another. The cooling system on an E-REV can be one of the most difficult tasks due to the varying temperature requirements for each of the components that require active cooling. In general, the overall complexity of developing an E-REV makes the process problematic and time consuming.

One of the major development challenges is packaging all of the components required for vehicle electrification. Some of the primary components that must be converted to run on electricity are the components that are on the front end accessory drive (FEAD) on a conventional vehicle engine. These components usually include the air conditioning (A/C) compressor, water pump, vacuum pump, power steering, and alternator. All of these components drain power from the engine thus reducing the overall vehicle performance, efficiency, and fuel economy. Electric versions of these components are therefore required due to the E-REV's all electric mode of operation. By replacing these accessories with electric versions, higher efficiencies are able to be achieved versus the mechanical versions. Conventional FEAD components typically account for between two and five percent of the fuel consumed on a conventional vehicle [8]. The new electrified components may require packaging in alternate locations with an E-REV, because typically they are mounted on the engine in traditional vehicles. Additionally, with the added electrified powertrain components the available space for sub-component integration is significantly reduced. Components such as an electric motor, electric motor inverters, high voltage battery charger, and high voltage battery occupy a significant amount of space in the vehicle. Due to this relatively large difference in typical vehicle design, properly designed and packaged electrified accessories are a critical task.

More importantly, cooling the components that are added to the vehicle as well as the existing components on a conventional vehicle can often be the toughest challenge developing an E-REV. For example, the operating temperatures vary greatly between high temperature components (e.g. engine) and lower temperature components (e.g. battery), which require properly designed cooling circuits. As a result, additional pumps, fans, and heat exchangers are often necessary because of the added components that require cooling. The necessity for additional pumps and fans for the thermal management of the electrical components can also add additional energy consumption to the overall vehicle. A 12 V electric pump can draw up to 20 A continuously, which can cause significant decrease in efficiency and fuel economy. Therefore, optimization of these components is critical to reduce as much energy consumption as possible while maintaining adequate cooling performance.

The primary method of optimizing the components and making them function properly is through controls and calibration. This process can be especially challenging with an E-REV due to the extensive communication network that must control all of the devices allowing the thermal system to function. In addition, it is imperative to ensure adequate vehicle operation and component temperature monitoring. During the control strategy development, all of the component temperatures must be considered when controlling the components that affect the thermal system performance. The calibration of the thermal system can be difficult and time consuming due to a large number of calibration values which control the thermal system. Narrowing down the calibration in a logical method can reduce overall development time, but the calibration is still very lengthy in duration and difficult.

Overall development of an E-REV is very complex because of all of these potential issues and challenges. The new components must be integrated into the vehicle along with most of the conventional components. All of the systems on the vehicle must function together and operate as intended. The thermal system must provide adequate cooling to every component and simultaneously minimize the amount of energy to provide adequate cooling. The entire vehicle must be safe, reliable, and provide significant fuel economy and emissions improvements.

1.3 Production Electrified Vehicle Issues

Several of production electric vehicles have gained media attention recently due to issues with either the electrical or thermal systems. The Fisker Karma, a low volume production range-extended vehicle similar to the MSU EcoCAR, has had issues with the high voltage battery pack. A123 Systems, Inc., the manufacturer of the faulty battery packs, blamed the problems on bad battery modules. In addition, A123 recalled the same battery packs for issues with internal coolant system components [9]. Shortly after releasing the Chevrolet Volt, General Motors did a voluntary recall to the vehicles adding structure around the battery pack and changing some cooling system components to further protect the battery pack in the event of a major crash [10]. While these problems were not related to the battery control strategy, they do illustrate how the overall complexity of creating high voltage batteries and electric vehicles creates significant challenges to engineers. These problems are resulting in a large investment in research to determine solutions for eliminating some of the potential dangers. Additionally, current predictions show a steady increase of electric vehicles on the road. According to Pike Research, the global market for EVs is predicted to rise to 3.8 million sales annually by 2020 [11]. Since more vehicles are electrifying and having problems with the thermal systems, this provided motivation for the study.

This study focuses only on the thermal system development over the three years of the competition. The study explains the design of the thermal system including the architecture selection, component selection, and integration considerations. The study also goes over the thermal system integration into the vehicle and the optimization that was performed through controls and calibration. The primary goal of the study is to have a thermal system that allows vehicle function during all driving conditions while at the same time minimizing energy consumption under normal driving conditions. The study also reveals the results of the thermal system performance at year two and year three competitions and how it impacted the overall vehicle performance.

CHAPTER II

THERMAL SYSTEM ARCHITECTURE AND DESIGN

As previously described, there were several components added to the vehicle that were all liquid cooled including three electric motors, three inverters, and a battery pack. Additionally, the 1.3 L GM diesel engine was also liquid cooled. All of these components needed to be taken into consideration when designing the thermal system. In addition, other variables associated with these components needed to be taken into consideration including the overall complexity, thermal requirements, maximum temperatures, and location in the vehicle. The entire vehicle thermal system was designed based on all of these different factors.

2.1 Design Considerations

2.1.1 Overall Complexity

The overall complexity of integrating the thermal system was evaluated when designing the thermal system. A simple yet effective coolant system was most important because there were so many components that were necessary for liquid cooling. There were several options for an overall layout. The components could be separated into multiple coolant loops, such as having the battery on one coolant loop and having the electric motors and inverters on another. However, this design option required additional coolant pumps and heat exchangers. This type of thermal system would require much more complex integration with existing space constraints. As a result, the best option was a thermal system that included all of the components in a single coolant loop. Utilizing this overall design presents its own challenges, and several other factors needed to be considered.

2.1.2 Maximum Temperatures

The components that needed to be integrated into the thermal system have different maximum temperatures. The maximum temperatures are very important to the normal operation of the vehicle. If a component reaches one of these maximum temperatures, that particular component will no longer function as intended.

The diesel engine operates at significantly higher temperatures than all of the electrical components; therefore, it must be on a completely separate coolant loop. For most effective cooling, the engine coolant loop must have the same system layout as the production vehicle. The A123 battery pack will begin limiting the power at 55°C and will completely shut off at 60°C. The electric motors and inverters will shut off as soon as they reach their unsafe limit and will not limit power. The maximum temperatures used for each of these components are shown in Table 2.1 below.

Table 2.1 Maximum component temperatures

Component	**Maximum Temperature**
Engine	100 °C
High Voltage Battery	55 °C
Electric Motors	100 °C
Motor Inverters	65 °C

Note: All three motors and inverters in the vehicle have the same maximum temperature.

2.1.3 Placement

Additionally, the components are located in different areas of the vehicle including the front engine bay, rear underside, and interior passenger compartment. First of all, the heat exchanger is required to be in the front of the vehicle to get adequate airflow. The battery pack placement is located at the rear of the vehicle with the coolant inlet and outlet located in the interior compartment below the rear cargo area. Two of the electric motors and inverters are located at the front of the vehicle, and the other electric motor and inverter are located at the rear underside of the vehicle. The arrangement of the components needed to be considered when designing the component placement in the coolant loop because these components are located in all areas of the vehicle.

If all of the components were placed in a series configuration, there would have to be several lines that are routed from the front to rear of the vehicle. As a result, unwanted mass would be added and it would significantly increase the overall pressure on the system affecting the coolant pump performance. By placing the electric motors and inverters in a parallel configuration, overall pressure rise decreases and limits the number of coolant hoses that are required to run from the front to rear of the vehicle. Additionally, the parallel configuration works well because the motors and inverters require a lower flow rate than the high voltage battery.

2.1.4 Thermal Requirements

By putting all of the components on one coolant loop, more heat is input into the system, and a single larger heat exchanger is needed. The thermal system was designed for a worst case scenario in which each component is operating at its maximum continuous power consumption. The vehicle does not operate in this condition, but it is a worst case scenario. Additionally, other loads on the vehicle high voltage system are also taken into consideration. A summary of the maximum power consumption is shown in Table 2.2 below.

Table 2.2 Maximum continuous power consumption

Component	**Power Consumption**
Front Motor	45 kW
Rear Motor	45 kW
Air Conditioning	5 kW
Miscellaneous	2 kW
Total	**97 kW**

2.1.4.1 Heat Generated by HV Battery

To calculate the amount of heat generated by the battery, the equation

$$\dot{Q} = I^2 R \tag{2.1}$$

was used, where $\dot{Q}$ is the heat generated by the battery, I is the current produced by the battery, and R is the internal resistance of the battery pack. An internal battery resistance provided by A123 Systems of 90 mΩ was used. In addition, the equation

$$P = IV \tag{2.2}$$

was used to find the corresponding power demanded from the battery, where P is the power demanded from the battery, I is the current produced by the battery, and V is the nominal open-circuit voltage of the battery pack. A nominal voltage of 363 V was used which was provided by A123 Systems. From this data, the following plot shown in

Figure 2.1 of heat generated versus power demanded by the battery is shown below. The arrow in this figure indicates the continuous power demanded from the battery and the corresponding heat generated by the MSU EcoCAR battery pack. This approximate value of 7 kW is the worst case scenario for continuous heat generated by the battery pack.

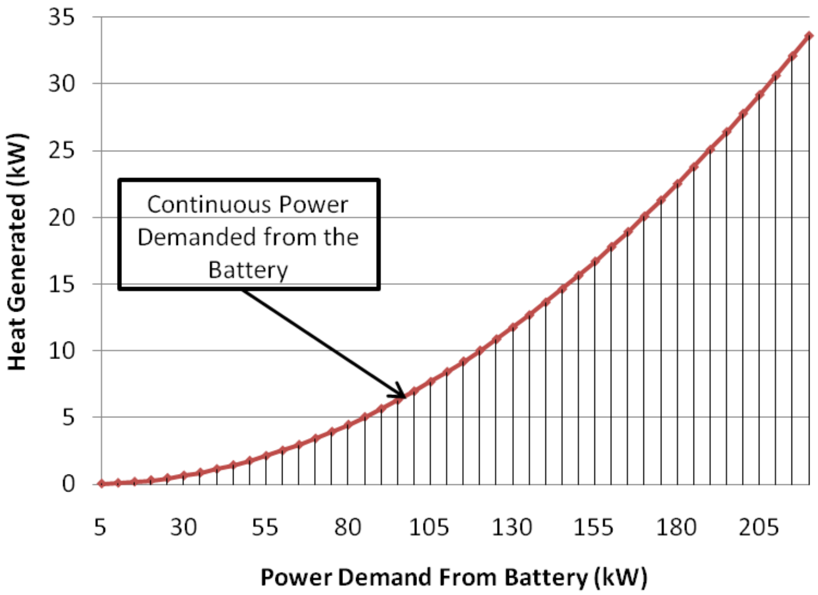

Figure 2.1 Heat generated by the high voltage battery pack.

2.1.4.2 Heat Generated by Motors and Inverters

In addition to heat generation from the battery pack, heat is also generated by the electric motors and inverters. Assuming a 45 kW continuous power output and 85% efficiency, a 6.75 kW design parameter for heat generated per motor and inverter was used. Based on this data, an appropriately sized heat exchanger was chosen for adequate cooling and size constraints.

2.2 Architecture

For the overall design of the electronics coolant loop, all of the above mentioned design parameters needed to be considered. The maximum component temperatures were critical factors when determining the order of the components in the coolant loop. Also, the location of the components in the vehicle was also an important factor to minimize the complexity and additional mass from excessive coolant hose. Based on the main factors, the arrangement of the electronics coolant loop that was designed is shown in Figure 2.2 below. The chosen design arranges the battery pack first in the coolant loop after the heat exchanger because it has the lowest maximum temperature. This allows the coldest possible coolant temperatures at the inlet of the battery pack. In addition, the battery pack is the most critical component necessary for vehicle operation. Without a functioning high voltage battery, the vehicle will not operate. However, if one of the electric motors or inverters overheats, the vehicle will still be able to operate on the alternate motor or inverter. The coolant system then splits into a parallel arrangement to help reduce system pressure and allow the coolant to go to different areas of the vehicle. The three parallel paths go to each of the three electric motor inverters. The three inverters, which convert the battery direct current (DC) to 3-phase alternating current (AC), have the next lowest maximum temperature of 65 °C and thus were arranged next in the system. Each inverter branch is followed by the corresponding electric motors which have the highest maximum temperatures. Afterward, the parallel branches combine back together into one fluid path. Finally, the fluid goes through the heat exchanger and the variable speed coolant pump.

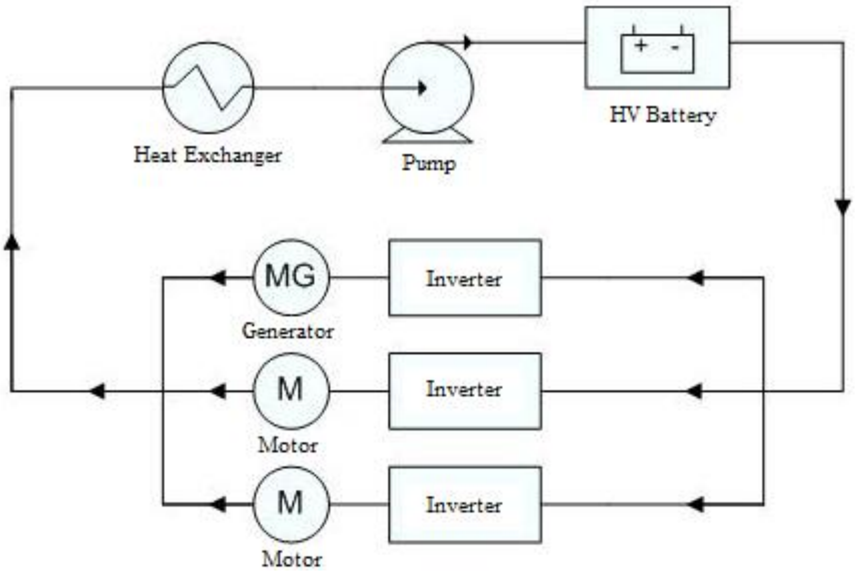

Figure 2.2 Thermal system schematic.

2.3 Supplementary Components

The coolant system is composed of several key components in addition to the major powertrain components. A custom heat exchanger uses ambient air to cool the fluid in the coolant loop. Airflow over the heat exchanger during low speed driving is provided by a variable speed electric fan. Fluid is pumped through the coolant loop by a variable speed electric coolant pump. Making use of the variable speed fan and pump can significantly reduce the total energy used during daily driving. The savings can lead to significantly improved fuel economy and all-electric range. An analysis of fan and pump power consumption was completed to determine optimal speed set points that maximize performance while reducing energy consumption.

2.3.1 Electric Coolant Pump

The electric coolant pump used for the electronics coolant loop is one of the two key components that allow for significant energy savings with the thermal system. The electric coolant pump is a CAN (Controller Area Network) controlled pump with variable flow rate capable of 25 gpm flow at 8.5 psi system pressure. There are many other advantages of this pump including a long life brushless motor, high efficiency, compact packaging, and high flow rate and pressure. The pump has an integrated controller and is powered on the 12 V system. At low speeds, the coolant pump has minimal power consumption. As the pump speed increases, the power consumption exponentially increases. This characteristic leaves room for significant improvements especially if a high flow rate is not needed. By staying in this low flow rate region, significant savings in energy consumption can be achieved. By operating the pump at 50% of maximum flow rate versus 100%, an 86% reduction of power is achieved. The measured electric pump power consumption can be seen in Figure 2.3 below.

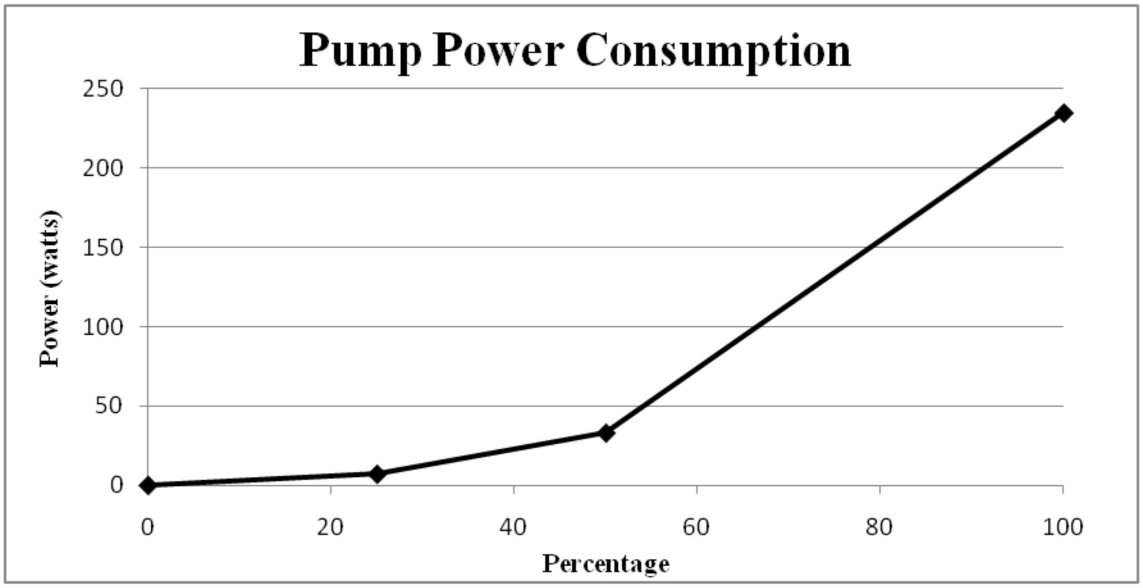

Figure 2.3 Electric coolant pump power consumption vs percentage speed.

2.3.2 Electric Fan

The electric fan, which is used to provide airflow over the heat exchanger at low speeds, also has variable speed capability. By varying the fan speed, significant energy savings can also be achieved. Variable fan speed is achieved with a pulse width modulation (PWM) signal sent by the vehicle controller. Similar to the electric pump, the electric fan uses significantly less power at lower fan speeds. During periods in which minimal airflow is needed, fan speed can be reduced and energy consumption can be minimized. For instance, by operating the fan at 50% versus 100%, a 78% reduction in power consumed can be achieved. The measured fan power consumption is shown below in Figure 2.4.

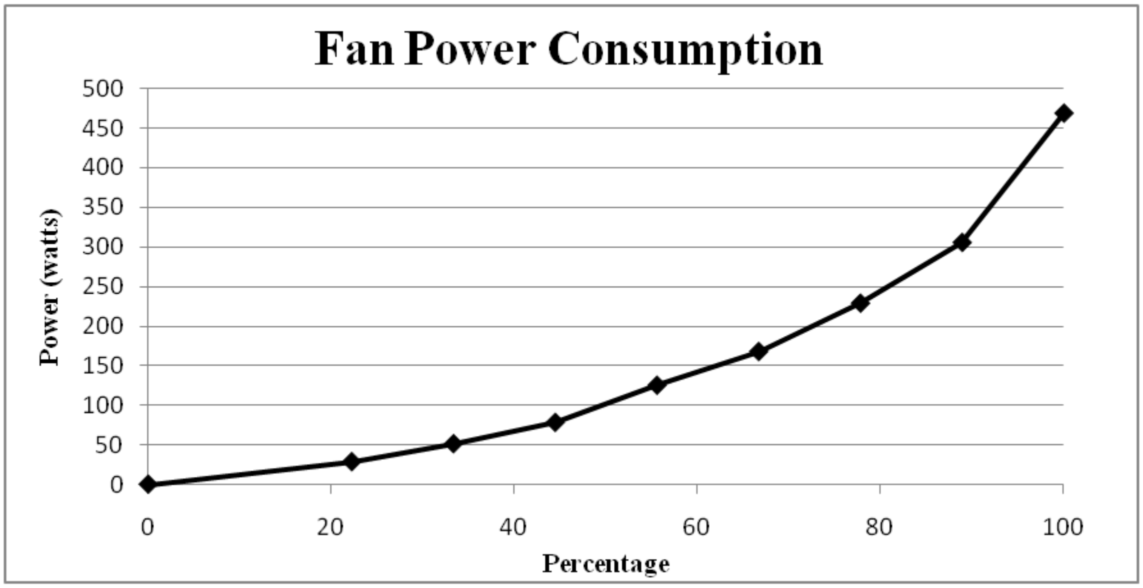

Figure 2.4 Electric fan power consumption vs percentage speed.

With all of the liquid cooled components, an effective and efficient thermal system is needed. The vehicle thermal system consists of two separate cooling loops. One loop is composed of the diesel engine and is setup in the same manner as the production vehicle. The second coolant loop, which has the variable flow coolant pump, is composed of the electrical components. The variable speed pump and fan can give noticeable energy savings by running the pump and fan at slower speeds when component temperatures are within limits. By running both components at 50% speed instead of 100%, a reduction of over 80% power can be achieved. During daily driving, the saved energy can lead to significant improvements in overall vehicle efficiency, and thus increase fuel economy and all electric range.

CHAPTER III

THERMAL SYSTEM INTEGRATION AND OPTIMIZATION

3.1 Integration

During the integration process, there were several challenges integrating the thermal system. To begin with, several of the components had different hose and fitting sizes. In addition, the compact integration of components in the engine compartment created space constraints. The two factors made routing and size conversions very difficult. Ultimately, all of the components were able to be integrated into the vehicle as designed. The integration differed from the design slightly because the three parallel paths were marginally different due to the different component locations in the vehicle. Therefore, the flow rate through each parallel path varied slightly. The electric coolant pump was integrated into the vehicle on the driver side frame rail near the heat exchanger. The variable speed fan was located just behind the heat exchanger at the front of the vehicle. The integration of the pump can be seen in Figure 3.1, and the integration of the heat exchanger can be seen in Figure 3.2 below.

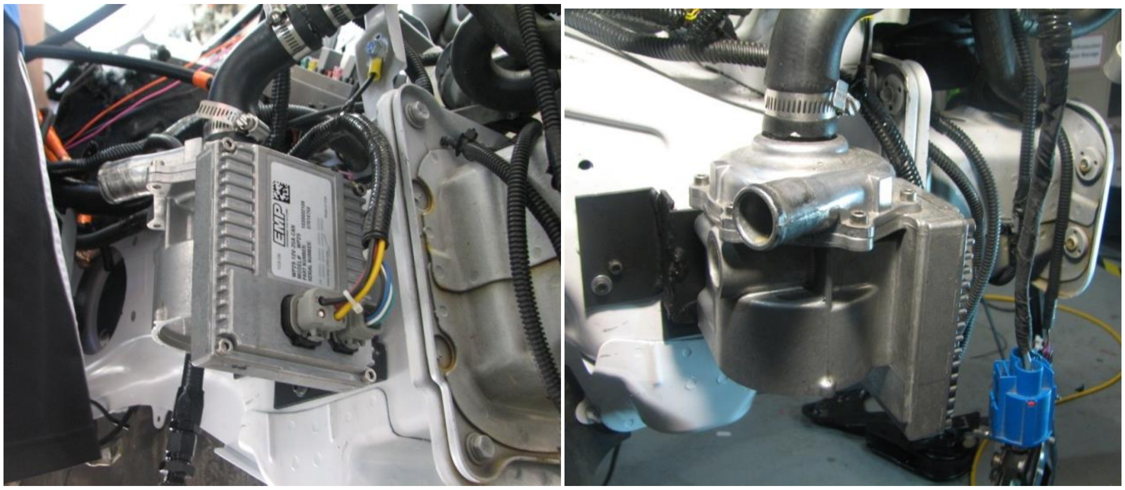

Figure 3.1 Electric pump integration into vehicle.

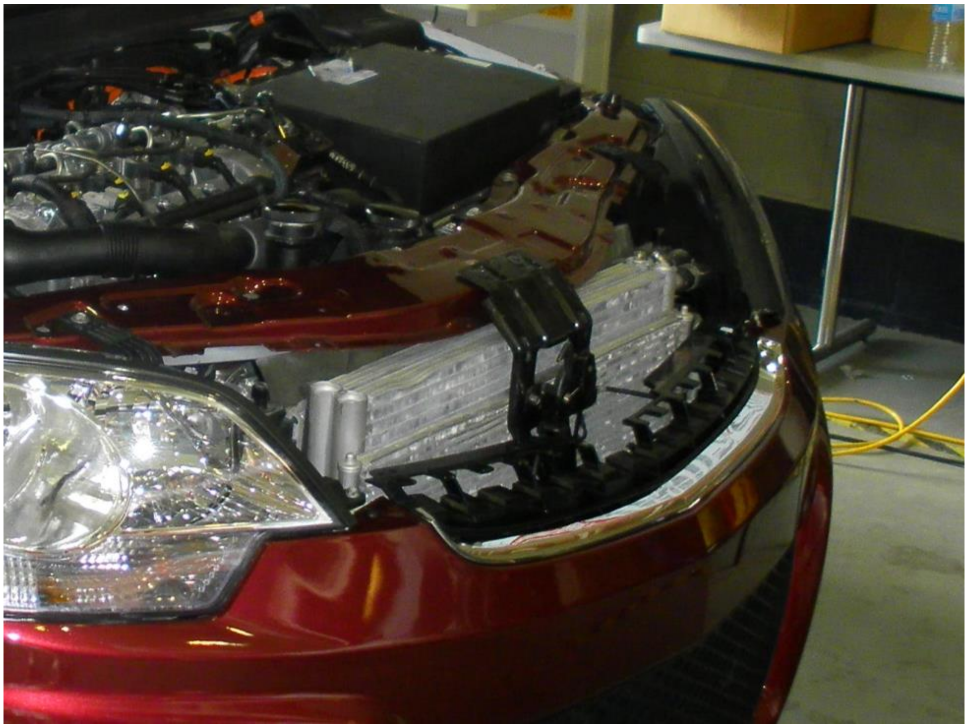

Figure 3.2 Heat exchanger and fan integration into the front of the vehicle.

Note: The heat exchanger can be seen in the image, and the fan is located behind this.

3.2 Control Strategy

Another key aspect of the vehicle thermal system is the control strategy. The vehicle thermal control strategy has several functions including monitoring component temperatures, adjusting fan speed, and adjusting pump speed. The controller communicates to the pump via Controller Area Network (CAN). If the pump loses CAN communication in the case of a fault, it will default to full speed, reducing efficiency but allowing continued safe vehicle operation until the system can be serviced. The fan speed is also controlled by the controller using a PWM signal.

The thermal control strategy was built in MathWorks Stateflow. Stateflow is a design environment integrated into MATLAB and Simulink used for developing control logic. It provides an efficient method to perform complex logical operations in an understandable format [12]. With Stateflow, there are “states” in which certain aspects can be controlled. Various factors can control the active state. The calibration parameters determine the movement between the states and function of each state. The Stateflow created to be used in the vehicle is shown in Figure 3.3 below.

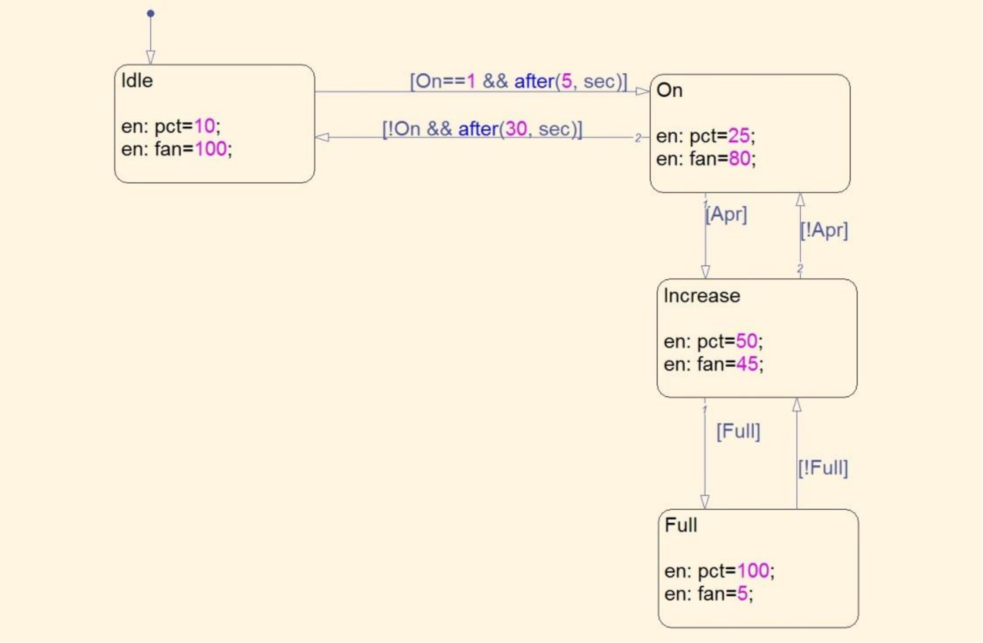

Figure 3.3 Thermal Stateflow strategy.

Table 3.1 Stateflow state descriptions

State	**Label**
0	Idle
1	On
2	Increase
3	Full

The thermal system has four states in which it operates. These states and their labels can be seen in Figure 3.3 and Table 3.1 above. When the vehicle is turned on, it always starts in the “idle” state. Ten different parameters can cause the system to move in and out of the different states. These parameters are the temperatures of the components on the coolant loop and include the battery, front motor inverter, front motor stator, front motor rotor, rear motor inverter, rear motor stator, rear motor rotor, generator inverter, generator stator, and generator rotor temperature. Different states have different values that cause the system to enter the particular state. The value associated with each component is a calibration value that can be easily changed, and the value was changed considerably during the testing and optimization process. The values are based on the particular components maximum temperature. The calibration is described in further detail later in the study.

Another parameter that controls the thermal system is the amount of fan and pump speed in the particular state. Each state in the thermal system strategy increases both the fan speed and pump speed. For instance, in the "idle" state, while component temperatures are well below limits, no or low fan and pump speed is possible. To eliminate hot spots in the coolant system, the coolant pump always has a minimal flow. During times in which component temperatures are very near maximum temperatures, the pump and fan speed need to be at full speed to prevent overheating.

Additionally, the states work in a forwards and backwards manner. If the thermal system enters a state because of a temperature increase, it will return to the previous state if the temperature drops below the limit. This often happens during periods of hard acceleration when the battery temperature spikes for a few seconds and then cools back down. An example of a hard acceleration test can be seen in Figure 3.4 below which shows the system behavior. As the battery temperature rises above the state transition set point of 45 °C, the system moves to the "full" state. After the battery temperature drops down below 45 °C, the system moves back down to the "increase" state.

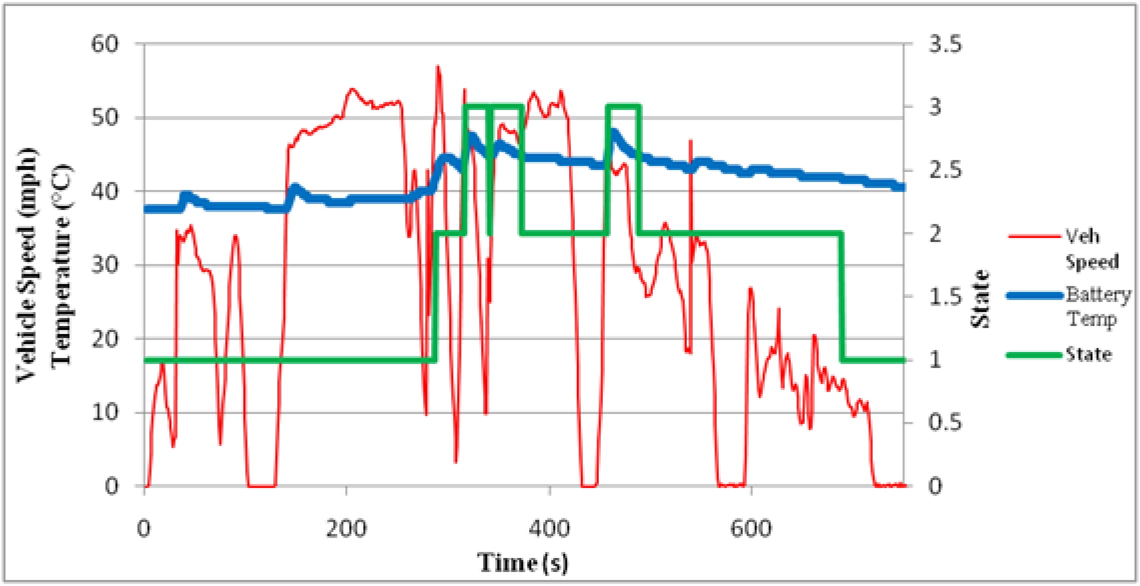

Figure 3.4 Hard acceleration test.

3.3 Optimization

The optimization process for the vehicle thermal system was completed over all three years of the EcoCAR competition. The baseline system described assumes components with equivalent power consumption but no variable speed capability. The configuration used for Year 2 competition utilized the variable speed pump and fan; however no optimization had been completed. To maximize energy savings, the variable fan and pump speeds in each state needed to be determined. In addition, improved temperatures at which the thermal system changes into the different states needed to be determined. These points control how long the vehicle is in each particular state. Testing both on road and on MSU's chassis dynamometer was used to perform the thermal system optimization.

3.3.1 Fan and Pump Speed

The fan and pump speed in each state is the main factor that controls the amount of energy savings. Both the fan and pump have significantly higher power consumption at full speed. To maximize efficiency, operation at this high speed needs to be minimized. For example, by operating both the pump and fan at 50% speed versus 100%, an 80% reduction in power consumption by the fan and pump can be achieved. Power consumption of the two components can be seen in Figure 3.5 below.

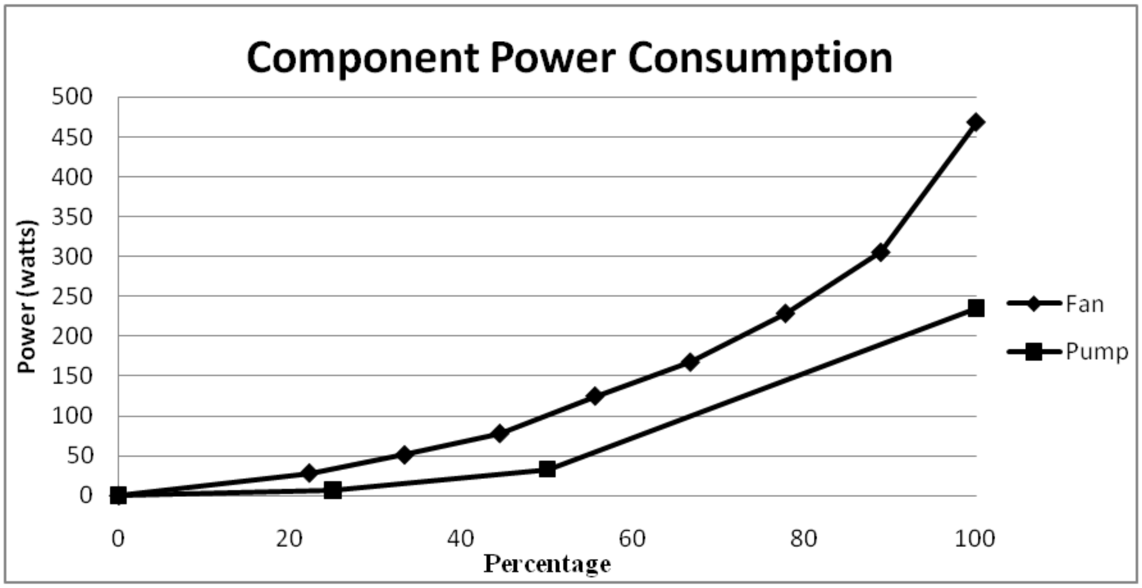

Figure 3.5 Component power consumption vs percentage speed

In the first "idle" state, it is not necessary to run the fan due to component temperatures being far from their maximum limits. In addition, to eliminate localized hot spots in the coolant, the pump should never be completely off; therefore, a very small pump speed is best. At very slow pump speeds the power consumption by the pump is very minimal. Prior to any optimization, both the pump and fan were in an 'off' state.

While driving with this setup, the system would not stay in this off state very long and it was determined useless. If driving conditions are not very stringent, then operating the pump a very small amount allows the system to operate in a low power consumption state for a substantial amount of time. The highest "full" state is when component temperatures are approaching maximum temperatures. In this full state, it is best to have both the fan and pump at full speed for maximum heat reduction. The other two states in the system had many options for pump and fan speed. The speeds for these two inner states range between the lowest speed and full speed for both components. The majority of fan and pump speed optimization was performed on a custom drive cycle that mimics a highway driving. A table summarizing the adjustment of the pump and fan speed can be seen below.

Table 3.2 Example of one iteration of adjustment of pump and fan speed for reduced power consumption

State	Run 1				Run 2			
	Pump (%)	Fan (%)	Power (watts)	Energy (watt-hr)	Pump (%)	Fan (%)	Power (watts)	Energy (watt-hr)
0	25	0	7	0.7	10	0	3	0.3
1	50	22	85	7.3	25	17	47	4.6
2	75	67	229	5.7	50	56	202	25.1
3	100	100	703.6	153	100	100	703.6	83.6

Note: The pump and fan column is the percentage of maximum speed of the particular component. The power is the amount of power used in the particular state. The energy is the amount of energy used in the particular state.

By changing the pump and fan speed percentage in each state, a reduction in energy consumption was achieved. Table 3.2 above shows one of the iterations that were performed to reduce energy consumption with the thermal system. Initially, the pump speed started at 25% in the first state and then continued in increments of 25% for each state. After testing the same drive cycle in the same ambient conditions, it was determined that a smaller increment percentage at the beginning and a larger increment as a last resort can save the most energy. By changing only the fan and pump speed in the different states a 32% reduction in energy consumed by the coolant system was achieved. Figure 3.6 below shows the drive profile that was completed for the above Table 3.2. In this plot, the battery temperature for the two iterations is shown along with the state of the thermal system. From the plot, it can be seen that changing the pump and fan speed did not affect the overall battery temperature drastically, but it did result in significant energy savings.

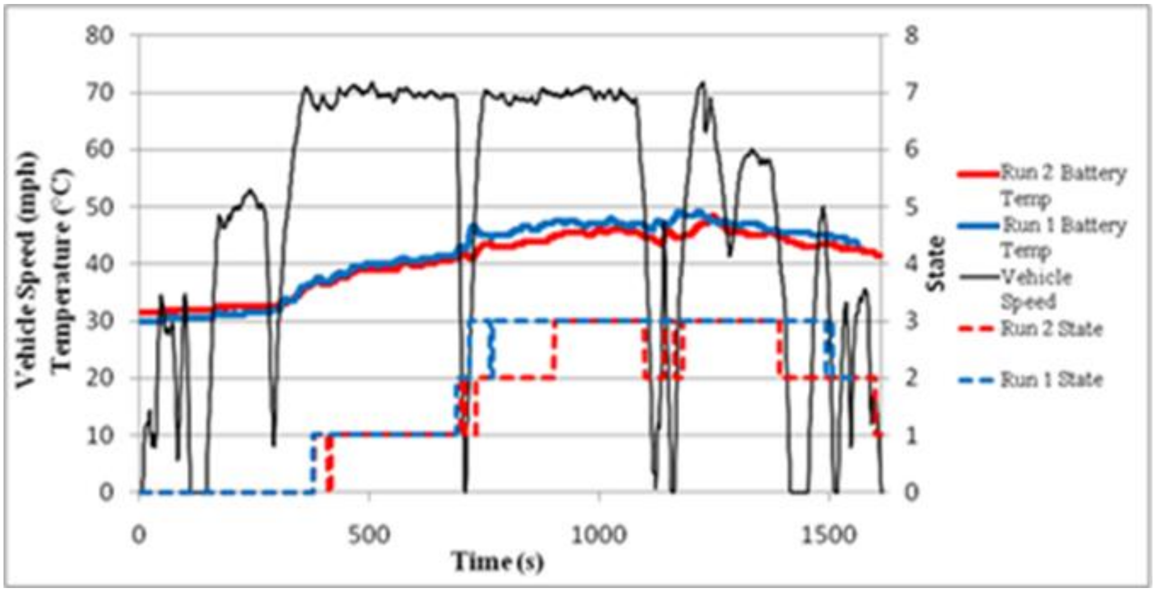

Figure 3.6 Energy use reduced by changing fan and pump speed in the states

3.3.2 State Transition Temperatures

The temperature parameters that affect the state transition are the primary factor that affects the length of time the thermal system stays in a particular state. By staying in the lower states longer, more energy can be saved. However, if the vehicle is producing too much heat, it must go into the highest state in sufficient time to keep the components cool. As soon as one component reaches one of the state transition temperatures, the thermal system will go into that state regardless of the other component temperatures.

Several iterations were performed during the optimization process to maximize the efficiency. Two of the iterations shown in Table 3.3 below indicate how the temperatures were adjusted for each state transition. The table also shows an adjustment for a malfunctioning temperature sensor on the front motor and generator inverters. The two components are older with an out of date firmware version. For the second iteration, the temperature to transition into "state 1" was increased for all of the components. The main temperature in which it was necessary to change was the motor inverter temperatures. The motors and motor inverters have a higher maximum temperature than the battery. The motor inverters operate at a higher nominal temperature and were causing the thermal system to enter the higher states prematurely.

Table 3.3 Adjustment of state transition temperatures for reduced power consumption

		State Transition Temperatures					
	Max Temp	Run 1			Run 2		
		State 1	State 2	State 3	State 1	State 2	State 3
Battery	55°	35°	40°	45°	37°	42°	45°
Front Motor	65°	40°	45°	50°	47°	52°	55°
Rear Motor	65°	35°	40°	45°	40°	45°	50°
Generator	65°	42°	45°	50°	47°	52°	55°

Note: Temperatures indicated are shown in degrees Celsius.

By increasing the transition temperatures significantly, it greatly reduced the thermal system power consumption. As shown in Table 3.4 below, a significant amount of energy was saved by optimizing the state transition temperatures. From the table, it can be seen that the system operates a longer time in the lower states, which reduces power consumption. A 73% reduction in energy consumption was achieved by changing these transition temperature values.

Table 3.4 Reduced energy consumption by adjusting state transition temperatures

State	Run 1			Run 2		
	Time (s)	Power (watts)	Energy (watt-hr)	Time (s)	Power (watts)	Energy (watt-hr)
0	40	3	0.03	865	3	0.72
1	1500	47	19.58	2694	47	35.17
2	2010	202	112.78	0	202	0.00
3	0	703.6	0.00	0	703.6	0.00

Note: The test results indicated above were on the MSU city test cycle. The time indicates the amount of time the thermal system operates in the particular state. The power is the amount of power used in the particular state. The energy is the amount of energy used in the particular state.

The behavior of the thermal system and system effect of changing the state transition temperature can be seen in Figure 3.7 below. This figure shows the vehicle drive profile that was used for this optimization. The drive cycle mimics a city drive cycle in which there is a lot of fluctuation in temperatures. The figure also includes battery temperature and the state that the thermal system was in. This figure shows how, prior to temperature adjustment, the state jumped to the higher state even though the battery was well within limits. The difference was due to low transition temperatures during the first states. Also shown in this figure is how the battery temperature stays within limits, even though the thermal system is not operating in the highest state.

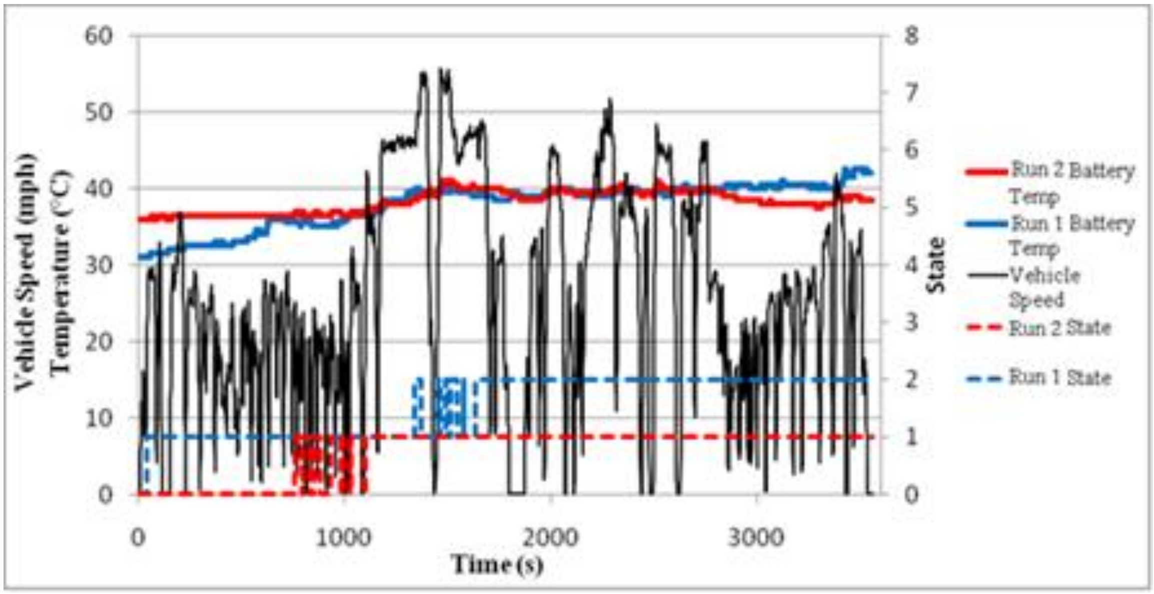

Figure 3.7 Energy use reduced by changing the state transition temperature

Note: The tests were performed on the same drive cycle under the same ambient conditions.

The thermal system integration and optimization was performed throughout year two and year three of the EcoCAR competition. For year two, the integration was completed, but no optimization had been done. For year three, optimization of the thermal system was completed. The optimization of the fan and pump speed along with the state transition temperatures resulted in significant energy savings over the two different drive cycles that were performed. By operating the fan and pump at slower speeds, energy savings of 32% over the MSU highway cycle were achieved. By operating in the lower states for a longer amount of time a 73% reduction of energy over the MSU city cycle was achieved.

3.4 Final Design

The final thermal system design consists of cooling all the electrical components on a single coolant loop. The system utilizes a variable speed coolant fan and pump. The thermal system can be in four different states with differing fan and pump speed. The thermal system monitors the component temperatures and transitions into the different states when a particular component reaches the set value. The fan and pump speeds that were chosen for each state can be seen in Table 3.5 below. Also, shown in Table 3.6 are the temperatures at which the system transitions between each of the states.

Table 3.5 Final design fan and pump speeds

State	Pump	Fan
0	10%	0%
1	25%	17%
2	50%	56%
3	100%	100%

Table 3.6 Final design state transition temperatures

Component	Max Temp	State 1	State 2	State 3
Battery	55	37	42	45
Front Motor Inverter	65	47	52	55
Front Motor Rotor	100	70	80	90
Front Motor Stator	100	70	80	90
Rear Motor Inverter	65	40	45	50
Rear Motor Rotor	100	70	80	90
Rear Motor Stator	100	70	80	90
Generator Inverter	65	47	52	55
Generator Rotor	100	70	80	90
Generator Stator	100	70	80	90

Note: Temperatures indicated are shown in degrees Celsius.

CHAPTER IV

RESULTS

4.1 Pre Competition Testing Results

Results of tests performed prior to competition are shown in the section below. The results show the performance of the MSU EcoCAR thermal system with the final thermal system calibrations on the vehicle. Three different drive cycles were performed to validate all possible scenarios the vehicle could experience at competition and during daily driving. The ambient temperature for all pre competition tests was roughly 32 °C. The three drive cycles replicate a hard acceleration drive cycle, a city drive cycle, and a highway drive cycle.

4.1.1 Pre Competition Acceleration Drive Cycle

Prior to competition, performance testing of the vehicle was completed. In this scenario, the battery pack is cycled with large amounts of current. In addition, the high speeds greatly increase the motor temperatures. When driving with this behavior, fuel economy is not a primary concern of the consumer. However, making sure that the vehicle components do not overheat is a major concern. Prior to the drive cycle, the temperatures of the components were in a preheated state to normal operating temperature. By doing this, the time it would take to heat up the components during normal driving was eliminated. The thermal system needed to be tested to make sure that it entered the higher coolant system state soon enough for the components to be adequately cooled. The performance test was designed to make sure that the vehicle would be able to withstand the acceleration and braking event at competition.

The drive cycle that was performed is shown in Figure 4.1 below. The several hard accelerations and brakes can be seen. Figure 4.2 below corresponds to the same drive cycle, but it shows the temperatures of the components in the vehicle that are on the electronics coolant loop. From this figure it can be seen that while the hard accelerations and brakes were being performed the temperature of the battery spikes significantly. From Figure 4.3 it can be seen that when the battery spikes the coolant system increases to the highest state. By going into the highest state, the vehicle is at its maximum cooling capability. From this figure, it can also be seen how the system started in “state 1”. This is due to the fact, as mentioned before, that the vehicle components were preheated. For this drive cycle, the battery temperature was the component that controlled the thermal system to go into the different states.

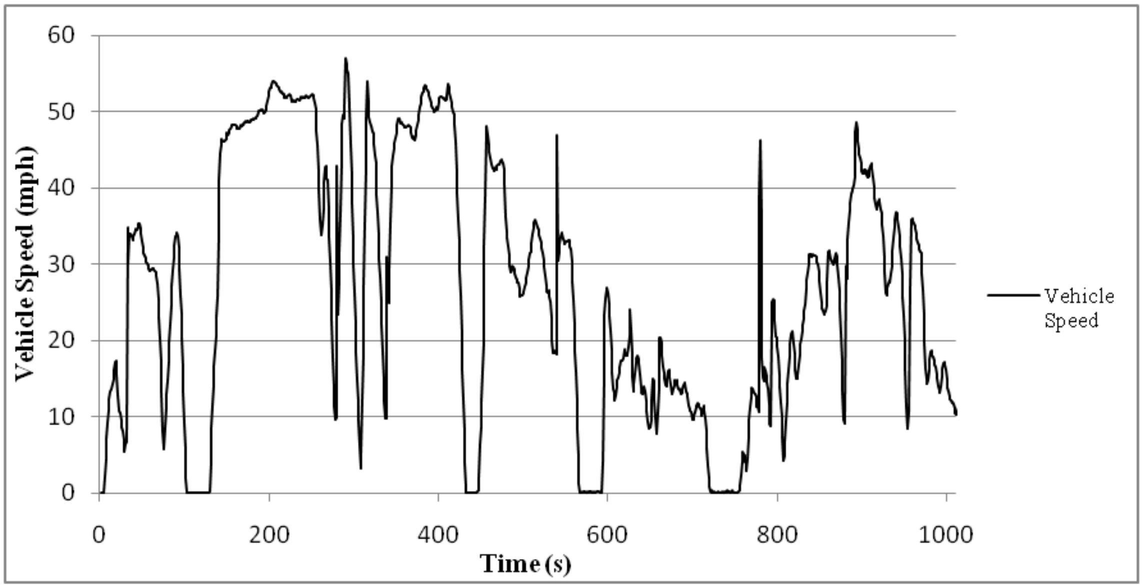

Figure 4.1 Custom acceleration drive cycle performed at MSU.

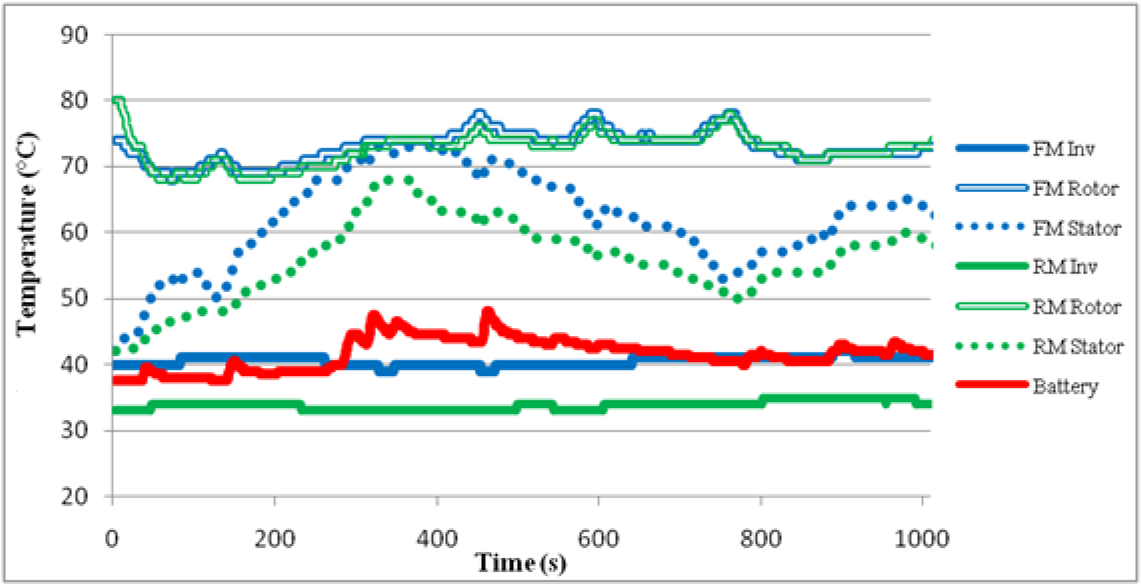

Figure 4.2 Component temperatures monitored by thermal system.

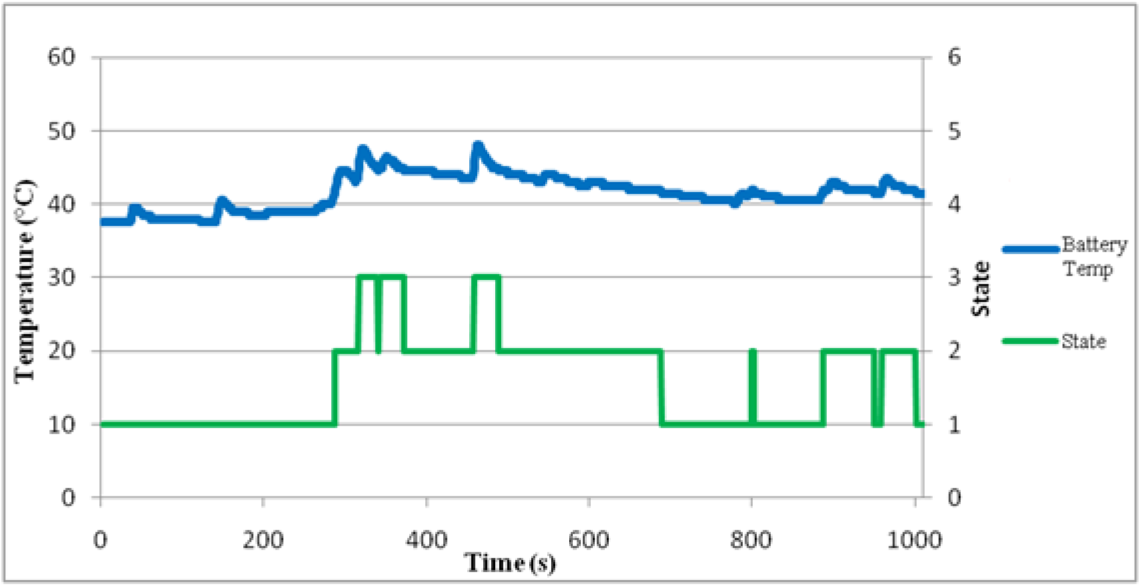

Figure 4.3 Battery temperature and thermal system state.

4.1.2 Pre Competition Highway Drive Cycle

Before competition, high speed testing on the vehicle used to simulate highway driving was performed. In this test, the vehicle was driven at 70 mph for an extended period of time. In this scenario, a fairly large amount of current is drawn from the battery pack, which produces a significant amount of heat. In addition, the electric motors get very hot due to the high operating speeds. Both energy savings and heat rise is important in this driving scenario.

The drive cycle used for this test shown in Figure 4.4 below indicates the steady state driving which was performed at a speed of 70 mph. The speed is significantly higher than the 58 mph maximum speed the vehicle is required to drive on the highway at competition. However, this event is used to simulate the towing event at competition. The increased speed takes into account the increased current due to towing the trailer.

The temperature of all of the components on the vehicle for this test is shown in Figure 4.5. From this figure it is shown that all temperatures stay within all limits. Figure 4.6 shows the thermal system state change into the different states caused by the battery temperature increasing. In addition, most importantly, as the system reaches the highest "state 3" the battery temperature begins to level off. The results from this drive cycle validates that the thermal system behaves properly and reduces energy consumption while providing adequate cooling to the components.

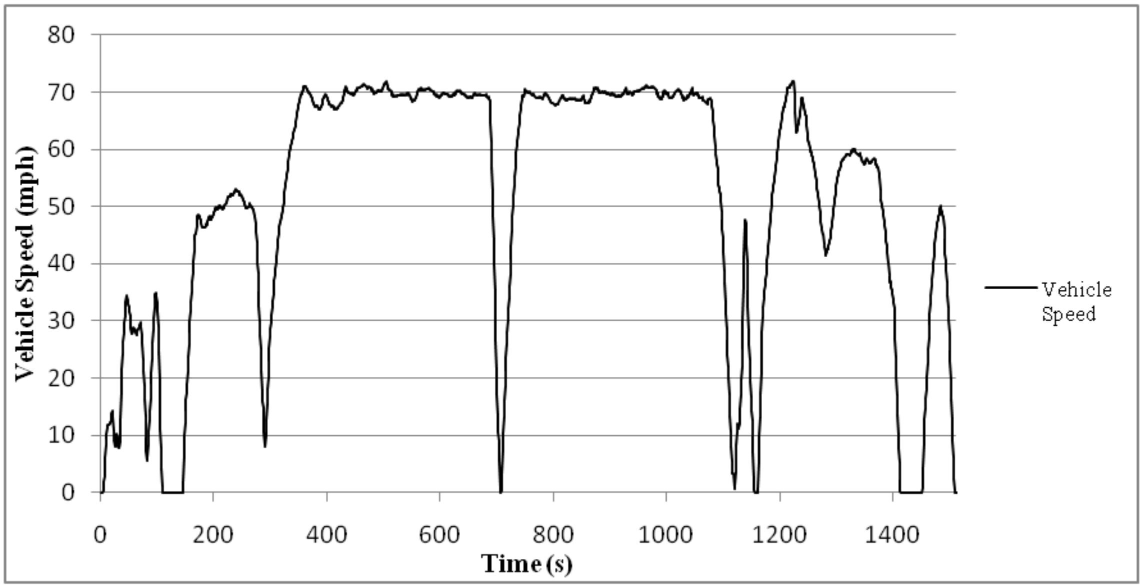

Figure 4.4 Custom highway drive cycle performed at MSU.

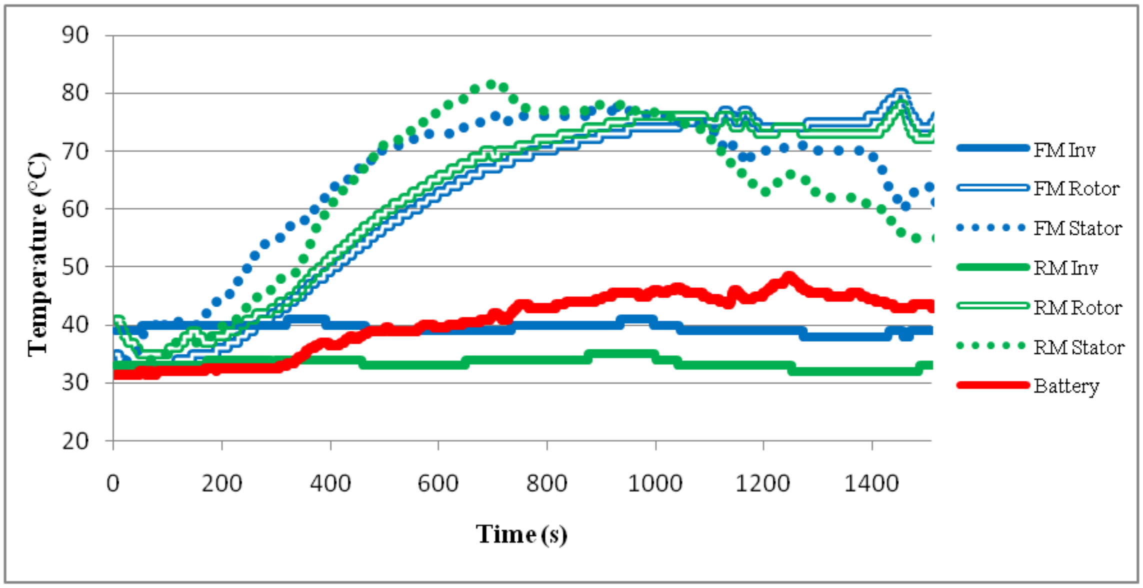

Figure 4.5 Component temperatures monitored by thermal system.

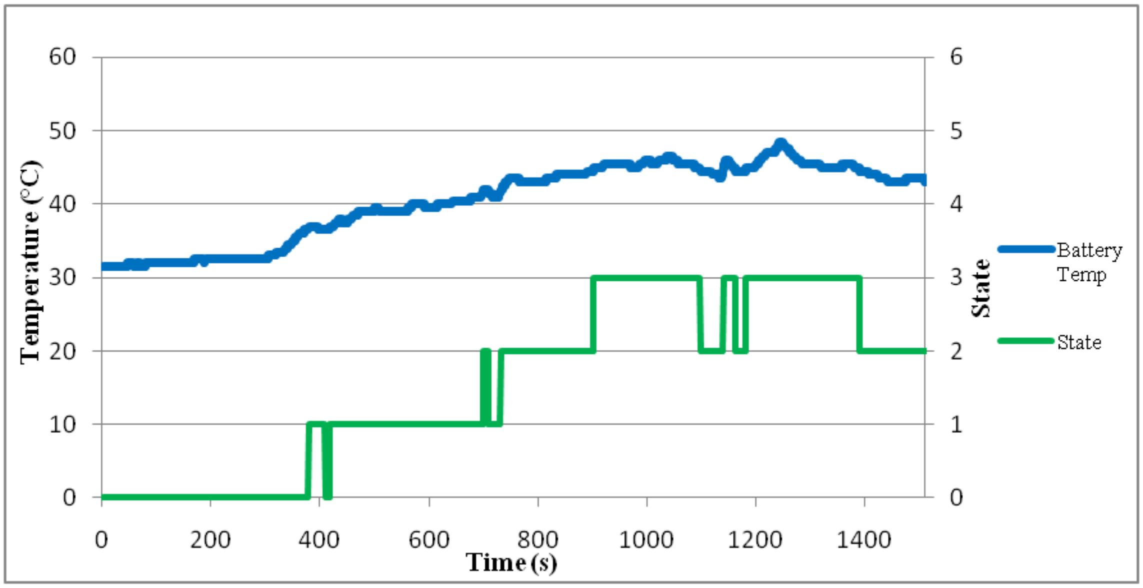

Figure 4.6 Battery temperature and thermal system state.

4.1.3 Pre Competition City Drive Cycle

The primary drive cycle completed before competition was a custom city drive cycle designed to maximize efficiency during the fuel economy and emissions event at competition. The vehicle emissions and fuel economy (E&EC) event at competition is the event that is worth the most points for competition and is where maximum efficiency is needed. Every small amount of energy that is saved over the entire event improves both the range and fuel economy. During this event high amounts of current are not required out of the battery pack or very high vehicle speeds. The purpose of this drive cycle was to make sure that the thermal system remained in the lower states during low speed city driving.

As shown in Figure 4.7, the vehicle speed replicates a city driving style with relatively low vehicle speeds. From Figure 4.8, the temperatures of the components on the vehicle are shown. Over the one hour drive cycle, none of the component temperatures required the thermal system to go into “state 2”. The motor rotor and stator temperatures are increasing, but they only rose 30 °C and are still 30 °C from the maximum temperature. The battery temperature stays low over the entire drive cycle. The battery temperature can be seen in Figure 4.9 below. From this figure, it can be seen that once the battery temperature reaches 37 °C, it went into “state 1” and never changed. This behavior shows that during city driving “state 1” provides adequate cooling to the vehicle. It also validates that the thermal system design maximizes efficiency during driving while maintaining the vehicle components temperatures far from their maximum.

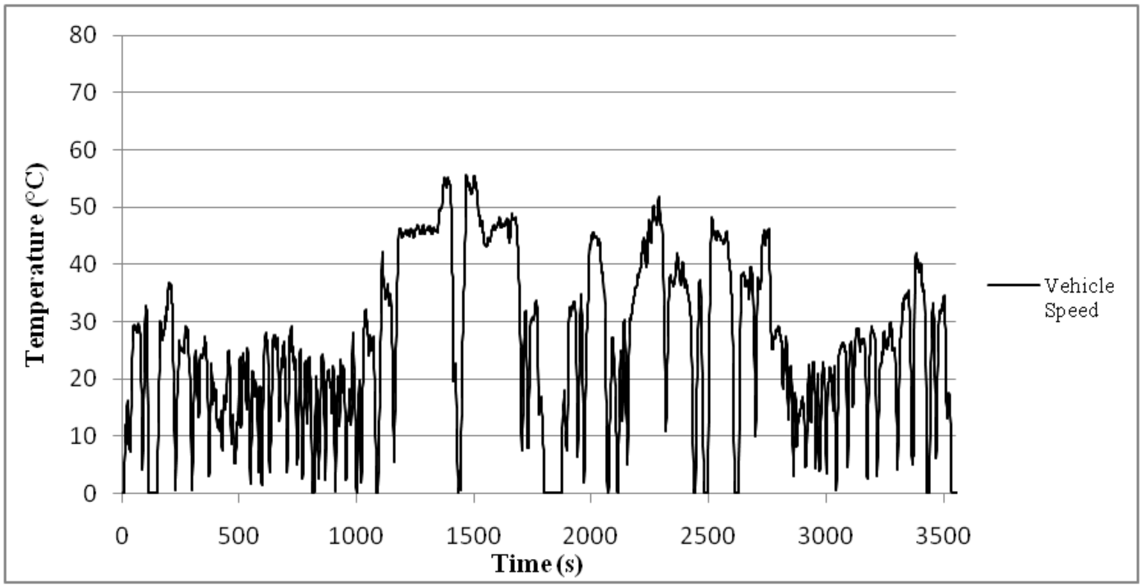

Figure 4.7 Custom city drive cycle performed at MSU.

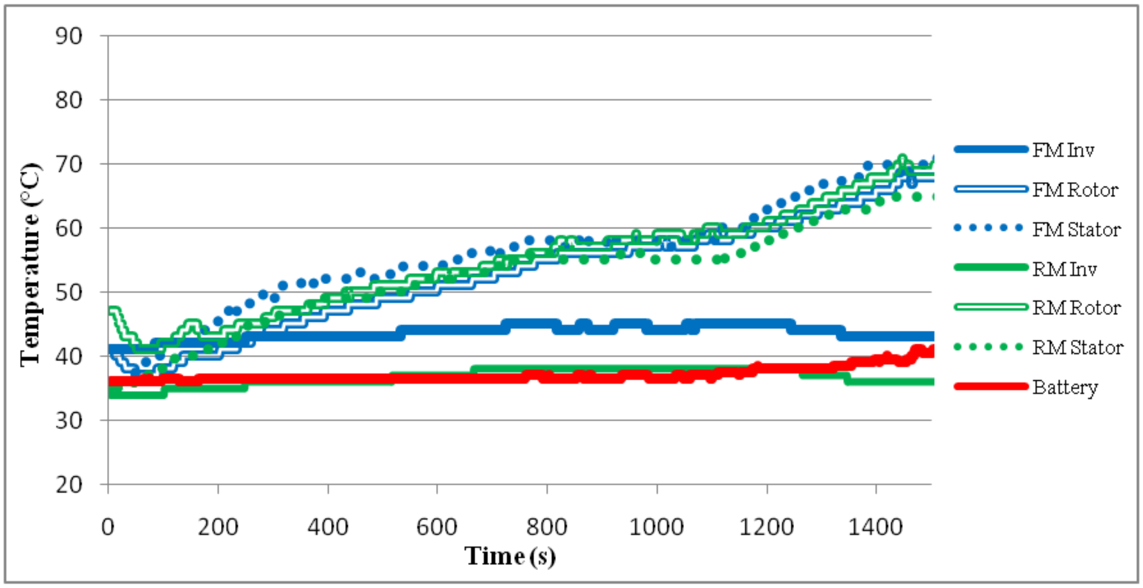

Figure 4.8 Component temperatures monitored by thermal system.

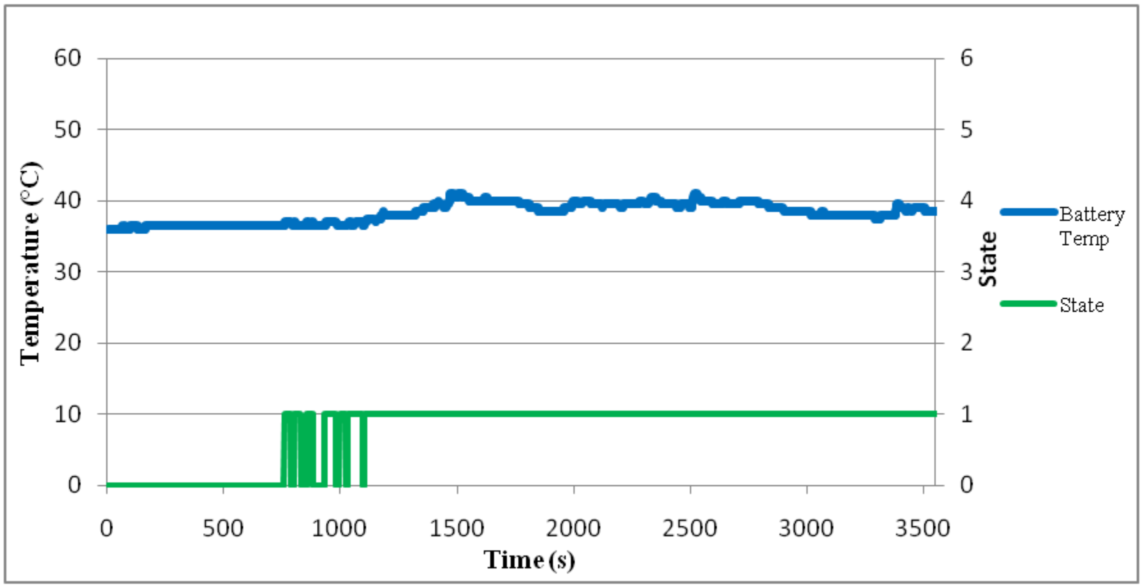

Figure 4.9 Battery temperature and thermal system state.

The above tests were completed prior to competition and were designed to prepare the vehicle for all of the competition events. It was important to make sure that the vehicle maximized efficiency by operating in low states when component temperatures were low while having additional protections ensuring the vehicle components stay cool during stringent driving conditions.

4.2 Competition Testing Results

Results of tests performed at competition are shown in the sections below. The results show the behavior of the vehicle thermal system with the same thermal system calibrations as the pre-competition testing. The sections below show the results of the events that are the most stringent on the vehicle thermal system. The ambient temperature varied at competition because the tests were run at different times of the day. The three events are acceleration event, towing event, and fuel economy and emissions event. The three events are designed to test the vehicle in city driving, highway driving, and performance driving. During these events, it was important that the thermal system provides adequate cooling and reduces the most possible energy consumed by the thermal system.

4.2.1 Competition Acceleration Event

The competition acceleration event tests the overall performance measures of the vehicle. This test consisted of four hard accelerations from 0 mph to 60 mph, four brakes from 60 mph to 0 mph, and four accelerations from 45 mph to 70 mph. During the periods of acceleration and braking, a large amount of current was drawn from the battery pack. Because the thermal system was designed for the continuous rated current, the significantly larger current causes spikes in battery temperature. However, the important factor of the thermal system is that it drops the temperature quickly enough for continued driving. The acceleration and braking event at competition was the most stringent on the vehicle thermal system.

The drive cycle performed at competition for the acceleration and braking event is shown in Figure 4.10. This figure shows the large spikes in vehicle speed and is fairly similar to the performance drive cycle completed before competition that was used to test the thermal system. Figure 4.11 shows the temperatures of the components over the acceleration and braking event. As shown in this figure, the battery temperature is the only component that increased in temperature significantly. The other components do remain stable, primarily because the short operating duration. Additionally, Figure 4.12 shows how the battery temperature affects the vehicle thermal system state. It illustrates that as the battery temperature increases, the thermal system changes states. In addition, the behavior of the battery temperature is demonstrated showing the spikes in battery temperature during each of the accelerations. Successful completion of the event without any overheated components validates the thermal system successfully cools the vehicles electrical components. In addition, the thermal system operated as intended by not operating in the highest states until higher vehicle component temperatures were reached. Furthermore, even though energy savings are not a primary concern for this event, the acceleration event yielded a significant increase in overall efficiency versus the baseline system.

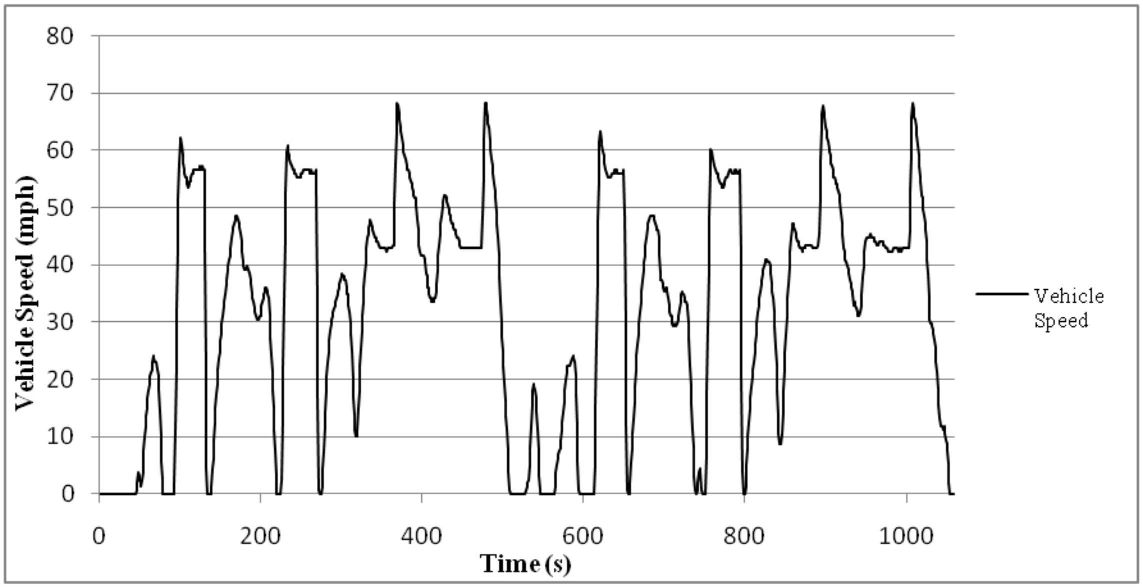

Figure 4.10 Acceleration event drive cycle performed at competition.

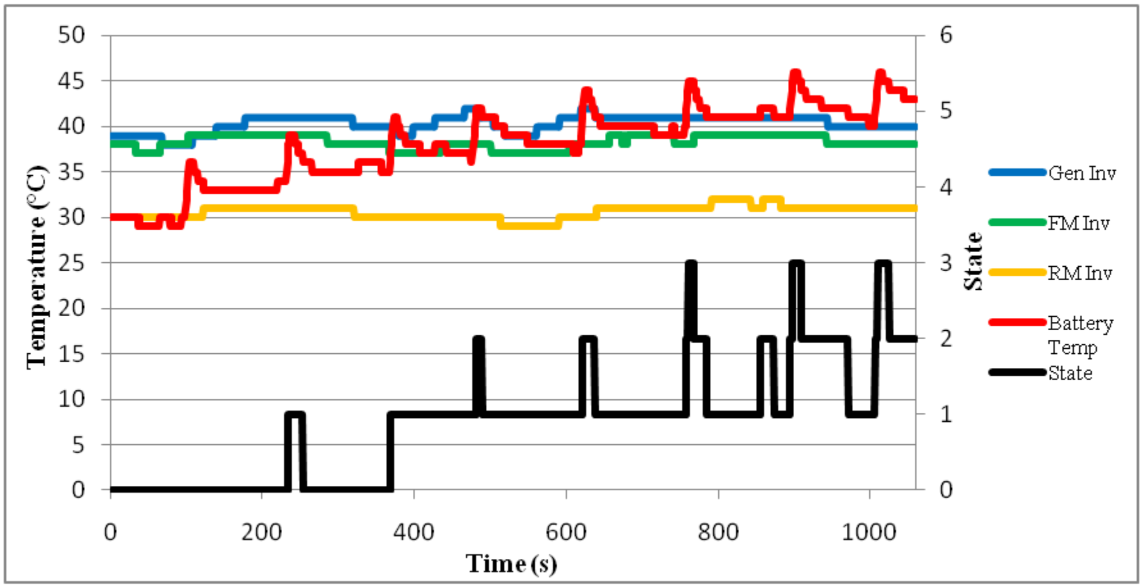

Figure 4.11 System state and component temperatures monitored by thermal system.

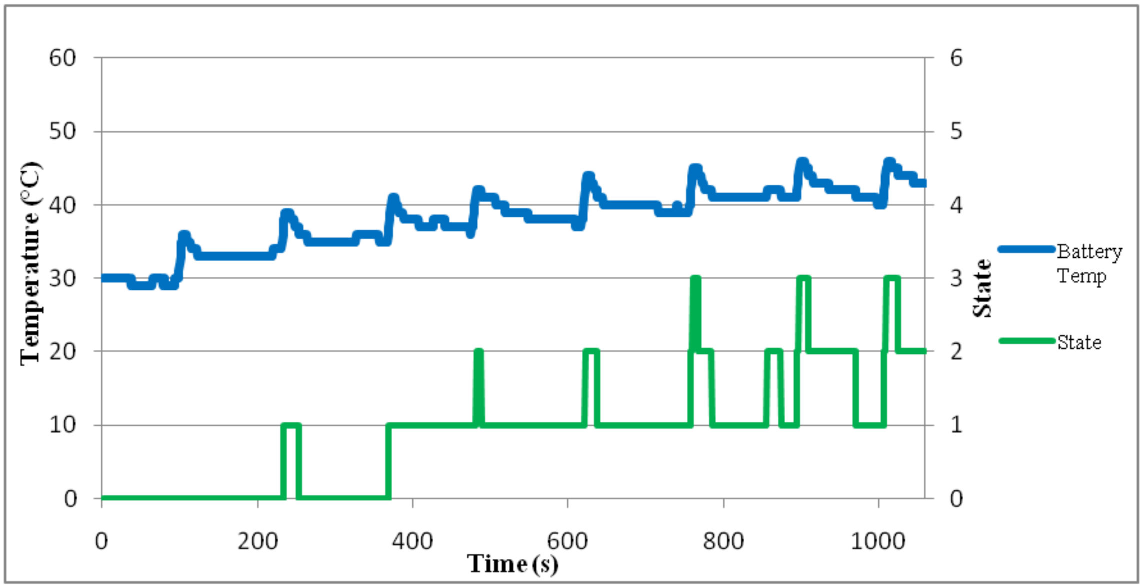

Figure 4.12 Battery temperature and thermal system state.

4.2.2 Competition Towing Event

The competition towing event is another event that stresses the thermal system design. This event pulls a significant amount of current out of the battery pack due to the towing of the trailer dynamometer. For this event, the vehicle tows a simulated 1500 lb load up a 3.5% grade for 15 miles and must remain above a speed of 42 mph. At the end of the event, an acceleration test from 40 mph to 65 mph was performed. The event tests the highway capability of the vehicle and the thermal system. The drive cycle tests the steady state capability of the thermal system to ensure that it can operate an extended period of time at high driving speeds without components overheating.

The drive cycle for the towing event at competition, shown in Figure 4.13, indicates that the vehicle drove at approximately 45 mph ending with an acceleration. The temperatures of the components over the drive cycle can be seen in Figure 4.14. All of the component temperatures are well within limits over the entire event. As shown in Figure 4.16 the battery temperature increased initially, however the battery temperature stabilized as the thermal system entered the first state. The thermal system stayed in the first state for the entire test until the end when the acceleration was performed. This behavior validates that the thermal system operates as intended. All of the components on the electronics coolant loop remained cool while reducing energy consumption over the event.

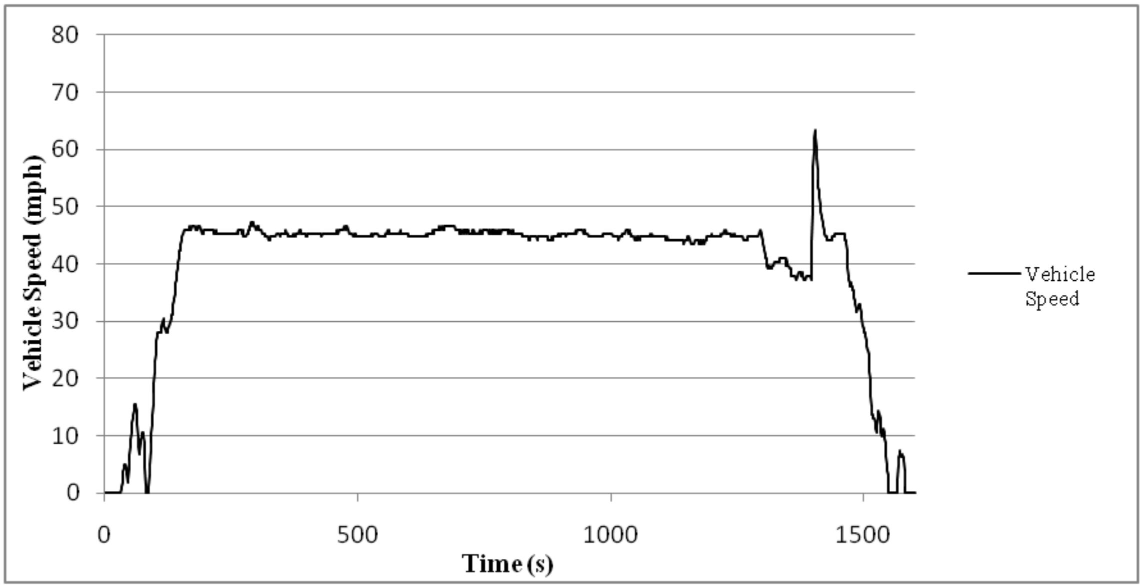

Figure 4.13 Towing event drive cycle performed at competition.

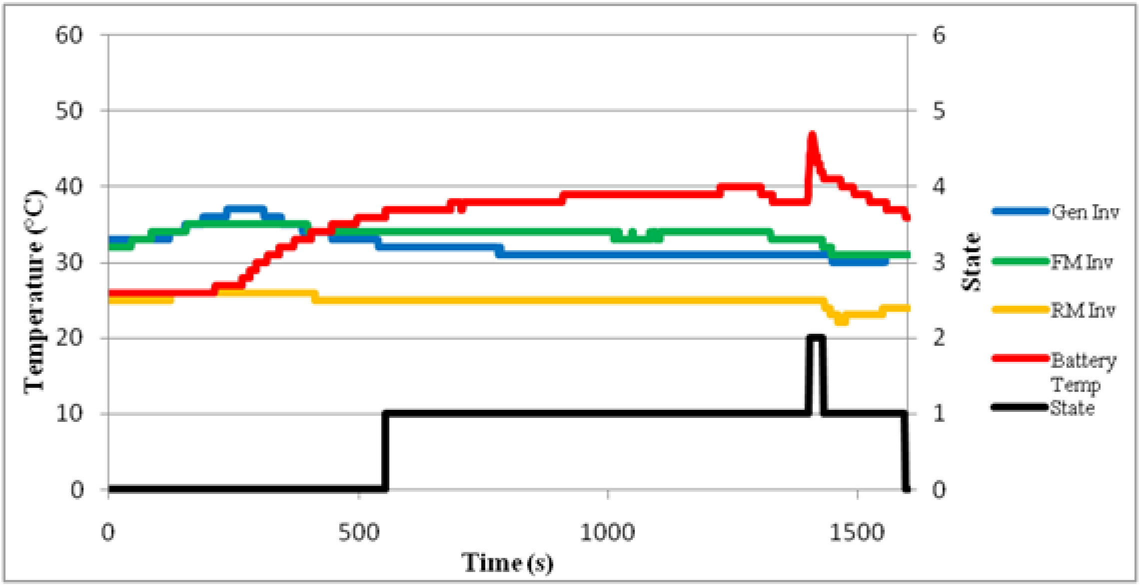

Figure 4.14 System state and component temperatures monitored by thermal system.

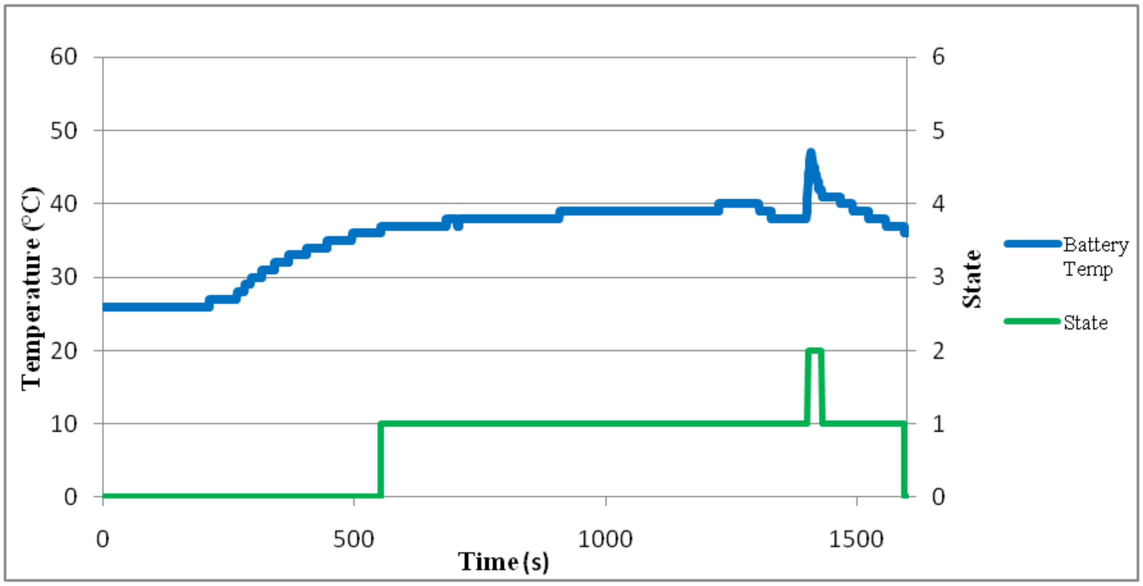

Figure 4.15 Battery temperature and thermal system state.

4.2.3 Competition Fuel Economy and Emissions Event

The fuel economy and emissions event at competition is the major event that affects the overall outcome of the competition. This event is worth over 420 points out of the possible 1000 total competition points. In this event four major vehicle metrics are measured including: fuel economy, well-to-wheel greenhouse gas emissions, well-to-wheel petroleum energy use, and tailpipe emissions. The vehicles all electric range is also found during this event. The E&EC event consists of a 103 mile drive cycle in which vehicle efficiency greatly affects the outcome. The most significant benefits to the thermal system design and strategy are realized during the event. The E&EC drive cycle is a combination of city and highway driving designed to replicate daily driving. There is not a large amount of heat generated by any of the components over this drive cycle; therefore, it is important that the thermal system operates in the lowest possible state.

The drive cycle for the E&EC event is shown in Figure 4.16 below. The repetitive city and highway portions can be seen. The temperatures of the components can be seen in Figure 4.17. The point at which the vehicle entered the charge sustaining mode of operation is shown. At this point, the battery temperature begins to stabilize due to the fact that most of the power supplied to the electric motors is from the engine and not the battery pack. This results in a spike of motor and generator temperatures. As shown in Figure 4.18, the primary factor that affects the thermal system state is the battery temperature. The thermal system also increases to “state 1” toward the very end as a result of the increased generator temperature. The thermal system stays in the initial “state 0” for almost the entire drive cycle. This behavior maximizes the amount of energy that is saved by operating in these lower states. These savings can significantly increase the overall vehicle efficiency. This behavior of the thermal system validates that the thermal system operated completely as intended.

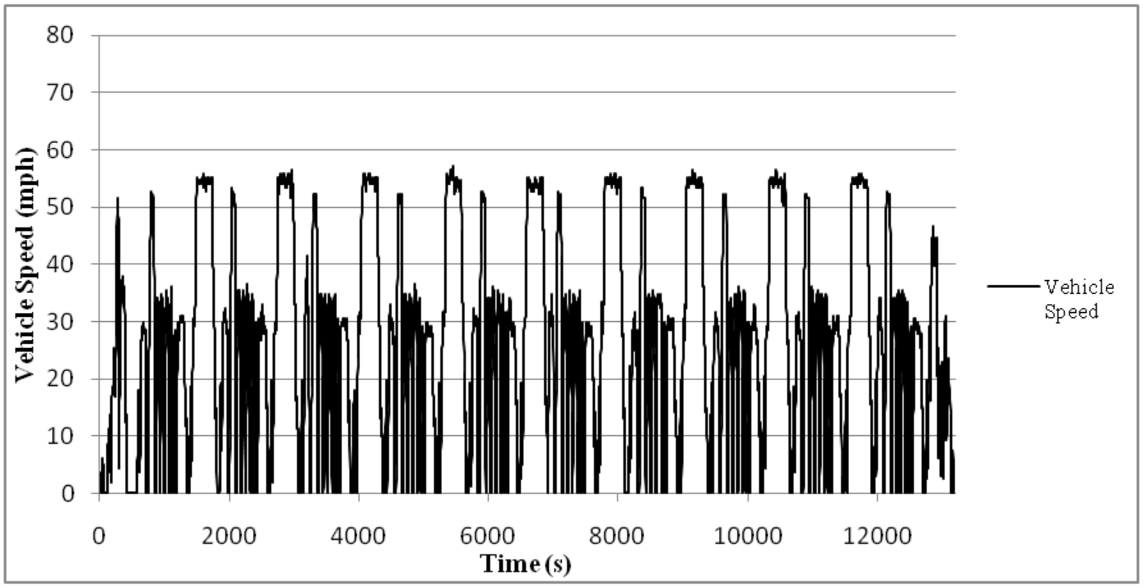

Figure 4.16 Fuel economy and emissions drive cycle performed at competition.

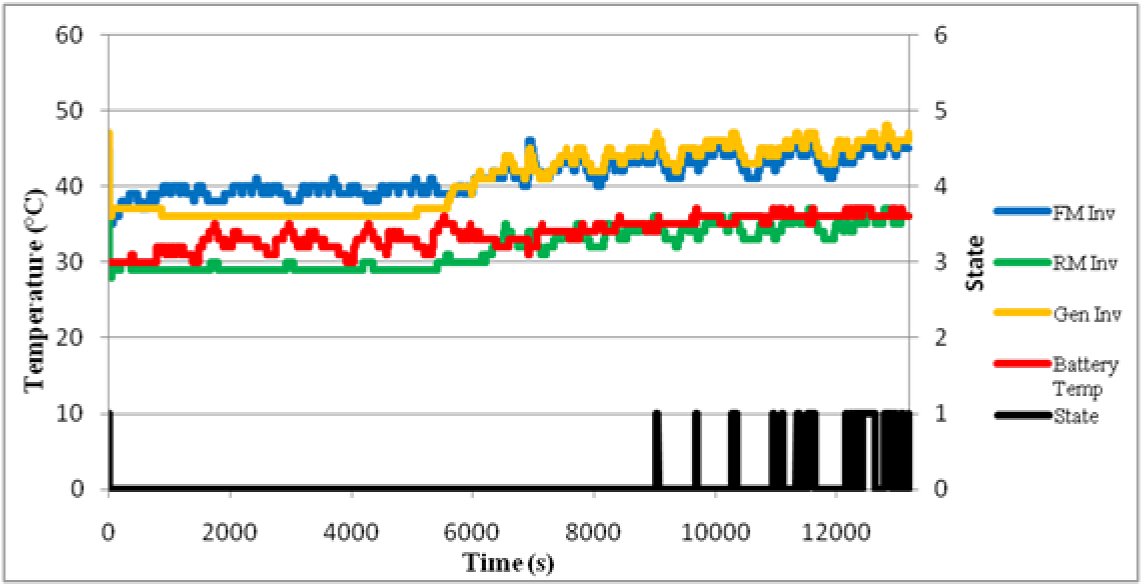

Figure 4.17 System state and component temperatures monitored by thermal system.

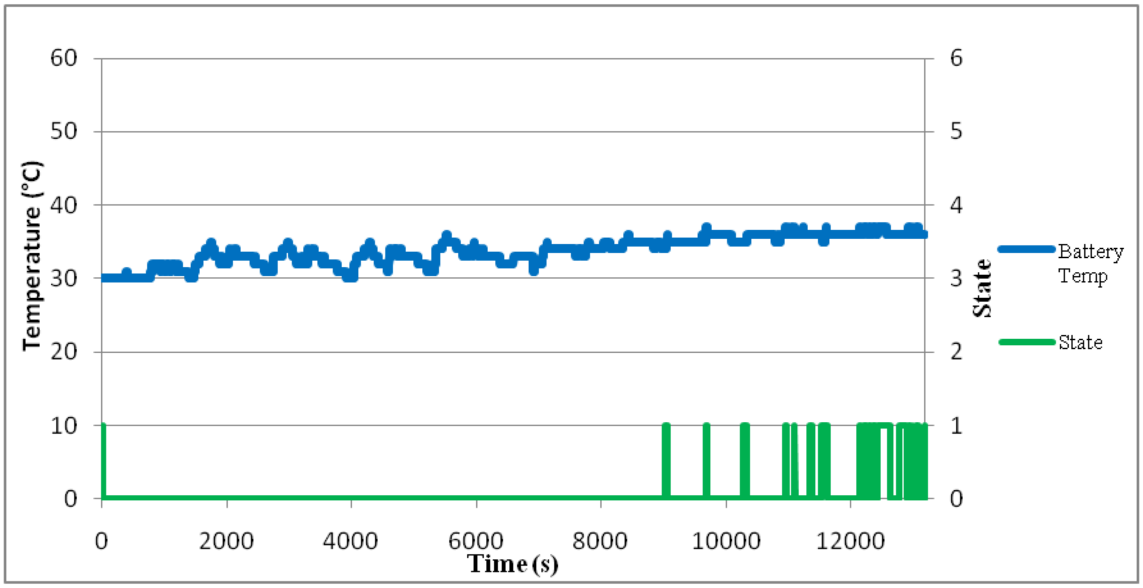

Figure 4.18 Battery temperature and thermal system state.

The results of the three competition events validate that the thermal system operates as designed because of their stringency on the thermal system. These results show that the thermal system ensures that the vehicle maintains safe component temperatures during all driving conditions that were tested both prior to and at competition. In addition, the thermal system strategy maximizes overall vehicle efficiency by reducing power consumption when a large amount of cooling is not necessary.

4.3 Energy Savings

By using the final design of the thermal system, a total of 2554 W-hr were saved over the baseline during the entire fuel economy event at Year 3 competition while 1085 W-hr were saved during the all-electric portion of the event. Additionally, savings of 875 W-hr over the total fuel economy event at Year 3 competition were achieved by using the final design of the thermal system over the system that was used for Year 2 competition while 220 W-hr was saved during only the all-electric portion of the event. The estimated energy consumption of the thermal system for the different phases of implementation is shown in Figure 4.19 below. A summary of some of the key factors that are related to the amount of energy saved, which affected the outcome of the competition are shown below in Table 4.1. Noticeable savings in all of these categories could have significantly affected the overall performance of the vehicle during this event and ultimately the competition results.

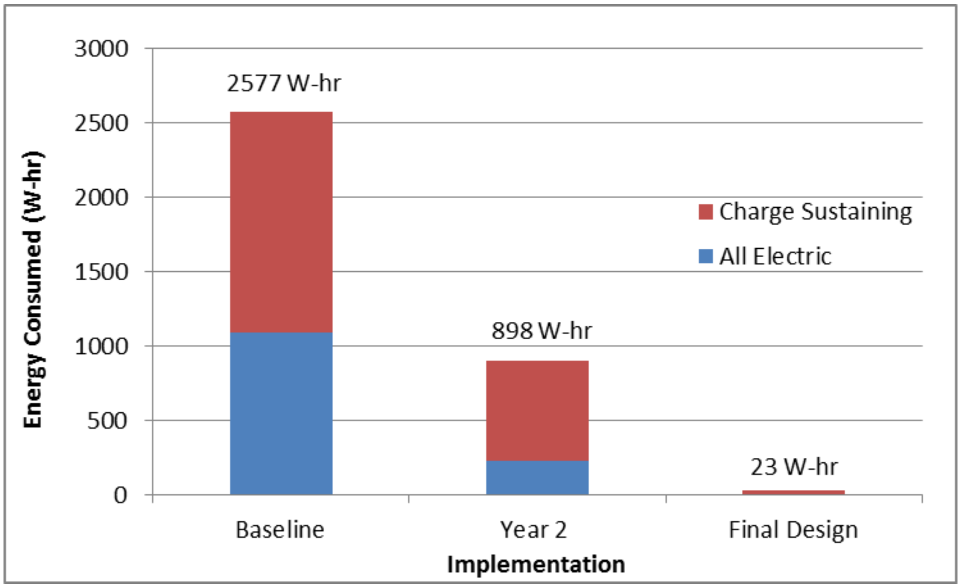

Figure 4.19 Energy used by the thermal system

Table 4.1 Year 3 vehicle improvements

		Implementation			% Improvement	
		Baseline	Year 2	Final	Final Design vs Y2	Final Design vs Baseline
Electric Range	(mi)	41.1	43.0	43.6	1.2%	5.9%
Fuel Economy	(mpgge)	45.8	47.7	54.2	13.7%	18.3%
WTW GHG	(g/km)	257.0	251.2	248.0	1.3%	3.5%
WTW PEU	(kWh/km)	0.41	0.40	0.35	11.7%	15.1%

Note: The values indicated in the table are estimated based on the amount of energy saved.

CHAPTER V

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

This thesis presented the design, integration, optimization, and validation of the MSU EcoCAR thermal system. Throughout the design phase, several factors were taken into consideration when choosing the best architecture for the thermal system. During the thermal system integration, many influences affected the overall integration. In the optimization phase, a considerable amount of time was spent calibrating the system for optimal efficiency and performance. The validation of the system was completed both before and at Year 3 competition through testing.

During the first phase of the design of the thermal system, numerous factors were taken into consideration including both vehicle and component requirements. The well-operating thermal system is critical to vehicle functionality. The basis for significant efficiency improvements was designed during this phase by selecting a variable speed coolant pump and variable speed cooling fan. By having the two components in the system, significant energy can be saved through reduction of the electrical loads while component temperatures are at safe levels.

Throughout the integration phase of the study, several challenges were presented that affected the other phases of the project. Space constraints were one of the primary factors that affected whether or not the design was able to be integrated. Additionally, there were also challenges due to having so many components with different size fittings and adapters. All of the challenges were solved by careful planning and integration.

The third optimization phase of the study was performed on the vehicle thermal system control strategy. The calibration values for fan and pump speed were the crucial variables that were optimized on the thermal system control strategy. The primary goal of the optimization was to reduce overall power consumption, while maintaining adequate heat rejection. Additionally, safety measures were put in place by operating the pump and fan at maximum speed when approaching any component over temperature limits. A 32% decrease in energy consumed by the thermal system was achieved at Year 3 competition versus the strategy that was implemented for Year 2 competition. An additional parameter that was optimized on the thermal systems is the temperatures the control strategy enters the different states of operation. By changing these state transition temperatures the vehicle operated in lower power consumption states for longer periods. As a result, a significant amount of energy is saved. Energy consumption, by changing these state transition temperatures, resulted in a reduction of approximately 73% of the energy consumed by the vehicle thermal system.

The final phase of the project was to validate that the vehicle thermal system operated as intended during all driving scenarios. Initial testing before competition on the road and on the MSU dynamometer helped validate the thermal system. However, the most important validation for the vehicle thermal system is that no over-temperature events occurred during any year three competition events. Every competition event that the vehicle participated in was completed without any issues with the thermal system.

Overall, the four phases of the project resulted in a total energy reduction on the vehicle of approximately 2554 W-hr on the E&EC competition event over a baseline thermal system. This correlates to approximately two miles additional all electric range, and eight mpgge improvement in fuel economy.

5.2 Potential Future Work

Due to limited time for testing the thermal system, additional tests focusing on only the thermal system would be beneficial. Additional data collected would improve the optimization of the thermal system. Further improvements in reduction of energy consumption could be achieved.

Further characterization of the components in the systems would also be valuable. By having detailed results of how much heat is input into the system, further tuning to the system can be performed. The electric motor manufacturer provides very little information about the electric motors and inverters that were used on the vehicle. Component tests on a dynamometer would have been advantageous to gather more data on the heat generated by the electric motors and inverters. Additionally, more data on the actual performance of the cooling plates on the inside of the battery pack would have been beneficial. Also, it is unknown where the temperature sensors inside the battery pack on the A123 modules are located. There were two different temperature sensors sent to the controller by the battery. The two temperature sensors measured significantly different temperatures during operation. This was most likely due to one of the temperature sensors measuring the battery cell temperature, while the other measured the busbar temperature. During periods of high demand on the battery, when the battery is using a lot of power, the busbar temperatures typically read significantly higher. Since the identification of the temperatures was unknown, the maximum temperature in the battery was used in the control strategy. This approach was the safest route to ensure no overheating, but it could have potentially been improved. All of this information would have been crucial to know to provide more accuracy when detecting temperatures and adjusting the calibration of the fan speed, pump speed and state transition temperatures.

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