1-1-2013

Supervisory Controller Validation For A Plug-In Parallel-Through-The-Road Hybrid Electric Vehicle By Software-In-The-Loop Testing

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SUPERVISORY CONTROLLER VALIDATION FOR A PLUG-IN PARALLEL-THROUGH-THE-ROAD HYBRID ELECTRIC VEHICLE BY SOFTWARE-IN-THE-LOOP TESTING

by

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THESIS

Submitted to the Graduate School

of Wayne State University,

Detroit, Michigan

in partial fulfillment of the requirements

for the degree of

MASTER OF SCIENCE

2013

MAJOR: ELECTRICAL ENGINEERING

Approved By:

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Advisor Date

DEDICATION

I will like to dedicate my work to my dad.

ACKNOWLEDGEMENTS

There are several acknowledgements that I will like to make. First, I would like to thank my fellow EcoCAR2 team members, past and present, especially my team leaders, Idan Regev and Kevin Snyder, and my advisor Professor Jerry Ku for all their guidance, patience and knowledge. EcoCAR2 and my academic growth would not have been possible without these three individuals' loyalty, perseverance and passion for engineering through the project. Also, I will like to thank Professor Le Yi Wang and Professor Caisheng Wang for being a part of my thesis committee and giving their time and attention to help me complete and present my defense. Additionally, I would like to thank my parents. They left everything, their homeland, families and friends to come to America to give my siblings and me the education they were never able to have. I would not be who or where I am today without their decisions, support, faith and love. Lastly, I would like to thank my best friend and boyfriend, Kashia. His enthusiastic, merry and positive personality never fails to lift my spirits.

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LIST OF ABBREVIATIONS

.m	MATLAB file
AER	All Electric-Range
APP	Accelerator Pedal Position
BCM	Battery Control Module
BEV	Battery Operated Vehicles
BodyCM	Body Controller Module
BPP	Brake Pedal Position
CAN	Controller Area Network
CD	Charge Depletion
CDMode_RWD	Charge Depletion Mode using motor only
CO2	Carbon Dioxide
CS	Charge Sustaining
CSMode_FWD	Charge Sustaining Mode using engine only
CSMode_Support	Charge Sustaining Mode using motor to support engine
DBC	CANdb network file (Data Base for CAN
DC	Direct Current
DFMEA	Design Failure Modes and Effects Analysis
E2D2	Ethanol-electric-dual-drivetrain (Wayne State Hybrid Warriors' vehicle nickname)
E85	Ethanol 85
EBCM	Electronic Brake Control Module
ECM	Engine Control Module
ECU	Electronic Control Units
EPA	Environmental Protection Agency
ESS	Energy Storage System
FCEV	Hydrogen Fuel Cell Electric Vehicle
FWD	Front Wheel Drivetrain
G1	Group 1 responsible for MIL and SIL testing
G2	Group 2 responsible for developing controller code
G3	Group 3 responsible for HIL and VIL testing
GM	General Motors
HCU	Hybrid Controller Unit
HEV	Hybrid Electric Vehicle
HIL	Hardware-in-the-loop
HV	High Voltage
HWFET	Highway Fuel Economy Test
ICE	Internal Combustion Engine
IMS	Internal Mode Switch
LE9	E85 compatible version of the General Motor’s 2.4 Liter Engine

m	Meter
MABXII	MicroAutoBox II
MIL	Model-in-the-loop
PHEV	Plug-in Hybrid Electric Vehicle
PRDNL	Pronounce as "Prindle" and is the driver shift lever used to select gears on an automobile equipped with an automatic transmission
PTTR	Parallel-through-the-road
RPN	Risk Priority Number
RWD	Rear Wheel Drivetrain
SAE	Society of Automotive Engineers
SC	Safety Critical
SEV	Series Electric Vehicle
SIL	Software-in-the-loop
SOC	State of Charge
TCM	Transmission Control Module
U.S.	United States
UDDS	Urban Dynamometer Driving Schedule
VDC	Volts Direct Current
VIL	Vehicle-in-the-loop
VTS	Vehicle Technical Specifications
WhlSlpSt	Wheel Slip Status
WSU	Wayne State University

CHAPTER 1. INTRODUCTION

1.1 Motivation

Today, the United States (U.S.) remains by far the largest consumer of oil. In 2010 the U.S. consumed approximately 804 million gallons of oil every day [1]. It is increasingly dependent on foreign oil; approximately half of the petroleum that the U.S. uses is imported and cost about $269 billion a year. Its dependence on imported oil will increase more over time as its domestic oil resources are depleted further as time passes [2].

Moreover, there is a growing recognition and acceptance that global climate changes are due to increased carbon dioxide (CO2) levels linked to the burning of fossil fuels. Automotive sector is powered almost exclusively by fossil fuels, which accounts for about 20 percent of the annual U.S. emissions of CO2. The average vehicle emits around 6 to 9 tons of CO2 each year. Every gallon of gasoline a vehicle burns puts about 20 pounds of CO2 into the atmosphere. Additionally, CO2 emissions can only be reduced by burning less fuel or by burning fuel that contains less carbon. Since fuel usage in vehicles is directly linked to CO2 release in the atmosphere, increasing fuel mileage actually decreases CO2 emissions overall. The difference between 25 miles per gallon and 20 miles per gallon amounts to a reduction in emission by 10 tons of CO2 over a vehicle's lifetime, or the equivalence of more than a year's worth of use [3]. For this reason, technologies aimed at improving fuel efficiency and displacing fossil petroleum are emerging to reduce petroleum dependency and CO2 emissions.

One of the leading candidate technologies is the hybrid electric vehicle (HEV) [4]. There are several advantages that HEV have over conventional vehicles. The first one is clean energy. An electric motor with a smaller gas powered engine working together results in lower emissions and better gas mileage. It conserves energy while having the power of a standard engine. The next advantage is performance improvements. New technologies allow hybrids the same kind of performance as normal cars, and they are continuing to be developed and improved to increase efficiency, get even better mileage, and reduce emissions even further. A third advantage is incentives. Varying from state to state and federally, hybrids may come with a tax benefit and savings in the form of much less money spent on fuel. A fourth benefit is regenerative braking. The battery is recharged during regenerative braking using the energy that normally will be wasted as heat in hydraulic braking. Additionally, HEV lowers fossil fuel dependence. Because they require less fossil fuel to run, they ultimately help to reduce the dependence on foreign oil. The last advantage is that HEV can be incorporated with a plug-in charger to reduce fuel use by offsetting fuel with stored grid electricity.

Modern automobiles utilize electric components to determine operations such as fuel delivery, transmission shift points and ignition timing [5]. Electric Control Units (ECUs) control all the electronic functions within the vehicle's drivetrain by taking readings from the vehicle components' electronic sensors and interpret its needs. For example, the Engine Control Module (ECM) is the ECU that is responsible for operating the engine. It is in charge of deciding and calibrating commands to the engine to perform accordingly such as making continual adjustments to the ignition timing to provide the proper air and fuel mixture for optimum engine ignition.

ECUs in conventional vehicles operated and made decisions on their own most of the times, only considering the driver primary demands such as accelerator pedal position (APP). This proves insufficient in hybrid vehicles due to the higher complexity of the additional powertrain components. HEV still needs to adhere to the increasing demands from customers and governmental regulations for better vehicle performance, drivability, and safety aside from fuel economy and reducing emissions. Hence, there is a need for a supervisory controller that has the ability to communicate and oversee all the ECUs [6]. The supervisory controller is a separate ECU that is responsible for translating the driver demands and various vehicle feedback signals from the existing ECUs to command signals to operate the powertrain subsystems of a HEV. It aims to ensure that the driver demands are met continuously and consistently while optimizing the powertrain efficiency and overall energy utilization without compromising vehicle safety [7].

1.2 Model-Based Design

The trend in the automotive industry has been toward more complex electronic control systems due to increasing quality and reliability demands. This increase the number of ECUs and complexity of communication networks in the vehicle. The traditional development process for vehicle electronics by depending on test vehicles for verification and validation is inefficient, because these errors in specification are often not discovered until final validation. Therefore high costs will occur to fix the errors due to specification change, redesign, re-implementation, and re-validation. Whereas, the model-based design (MDB) approach [8] allows the system to be tested in a virtual environment when they are inexpensive to fix before it is implemented or integrated on the final hardware. It has become an essential tool in design and validation because it reduces development cost and improves product quality even though the complexity of vehicle electronics rises.

Model-Based Design (MBD) is a mathematical and visual method of addressing problems associated with designing complex control and other engineering systems. Modeling and simulation tools have long been in use, but traditional text-based tools are inadequate for the complex nature of modern control systems, due to their inherent disconnect with graphical tools and their tedious “off-line” debugging setups. MBD meets all these challenges by offering an integrated graphical modeling environment. The MBD paradigm is significantly different from traditional design methodology. Under MBD development is manifested in these four steps: 1) modeling a plant, 2) analyzing and synthesizing a controller for the plant, 3) simulating the plant and controller, and 4) integrating all these phases by deploying the controller. This would allow the designers to define models with advanced functional characteristics, and the built models using simulation tools can lead to rapid prototyping, software testing, and verification.

There are intermediate integration levels between initial modeling and the integration into actual hardware in model-based testing: model-in-the-loop (MIL), software-in-the-loop (SIL), hardware-in-the-loop (HIL) and vehicle-in-the-loop (VIL). The first integration level is MIL which tests the software in a simulated environment without any hardware (i.e. no mechanical or hydraulic components, no sensors, and no actuators) and is run on the same machine, usually on a PC. First, the physical models of the powertrain components are validated individually among themselves. For example, the engine plant model with the soft ECM model is tested with simulated signals to ensure that the code is behaving as expected. After all the models are tested individually successfully, the entire vehicle plant model and controller model will be connected and MIL system tested together. The testing data flow can be seen in Figure 1-1.

This validation will be very abstract and do not consider all aspects such as robustness and performance. The resulting plant models are tested to meet the requirements of the supervisory control strategy only. The second integration, SIL design starts with MIL and transitions to SIL when physical I/O that has been defined to exist in the actual vehicle are taken into consideration in its design process as seen in Figure 1-2.

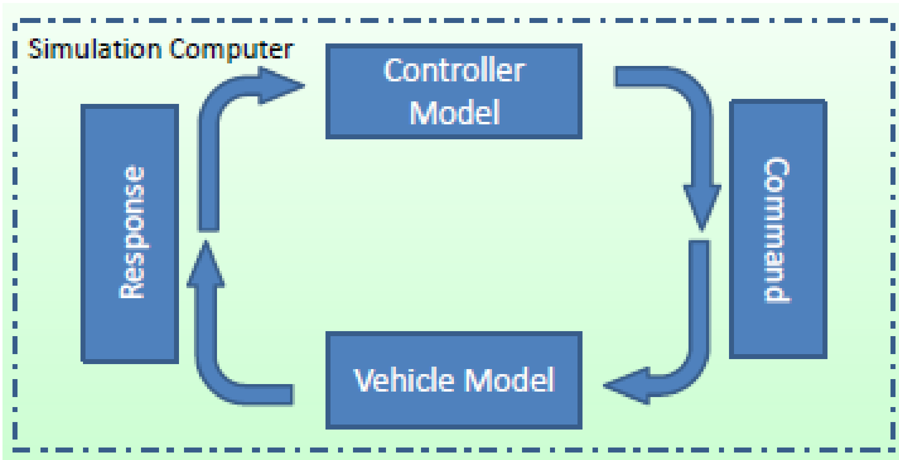


Figure 1-1. MIL (Model-in-the-loop) Data Flow [9]

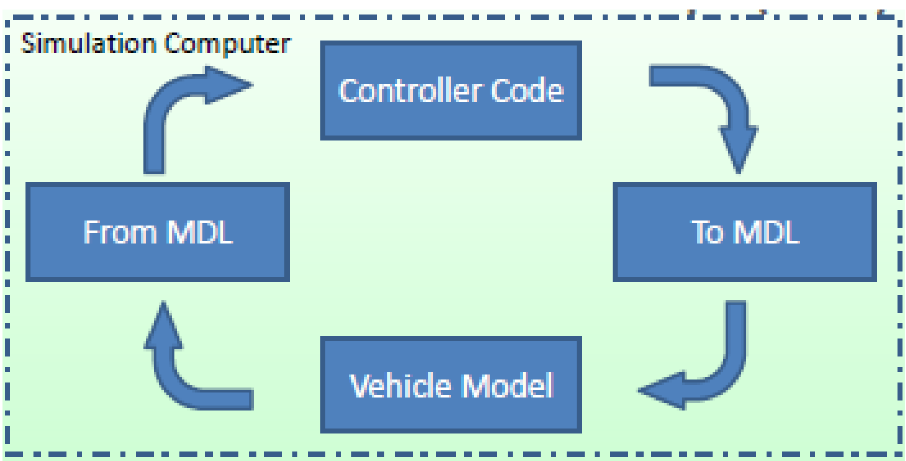


Figure 1-2. SIL (Software-in-the-loop) Data Flow [9]

The third integration level is HIL. It involves real-time testing with physical interfaces between the actual controller and simulated components. The actual controller is programmed with the software being tested with a real-time vehicle simulator as seen in Figure 1-3. The simulator is a dedicated processor board system with physical interfaces. Typical peripherals such as controllers, sensors, actuators and any needed controller area network (CAN) buses can be wired to the simulator as vehicle components to emulate the actual vehicle. Computer models can be uploaded into the simulator to imitate major vehicle components such as engines and electric motors. The real-time simulation results are available at the Host PC [10]. Lastly, VIL is the real-time testing with the physical components of the actual vehicle [9] as seen in Figure 1-4.

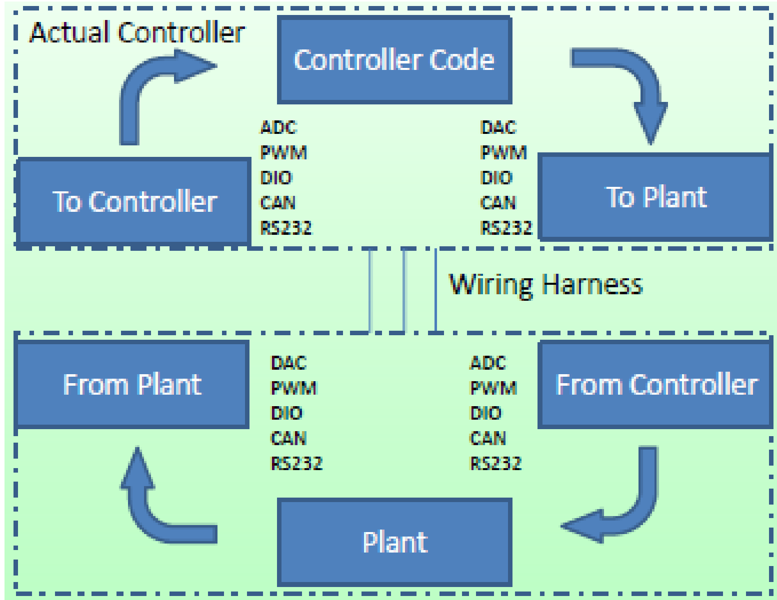


Figure 1-3. HIL (Hardware-in-the-loop) Data Flow [9]

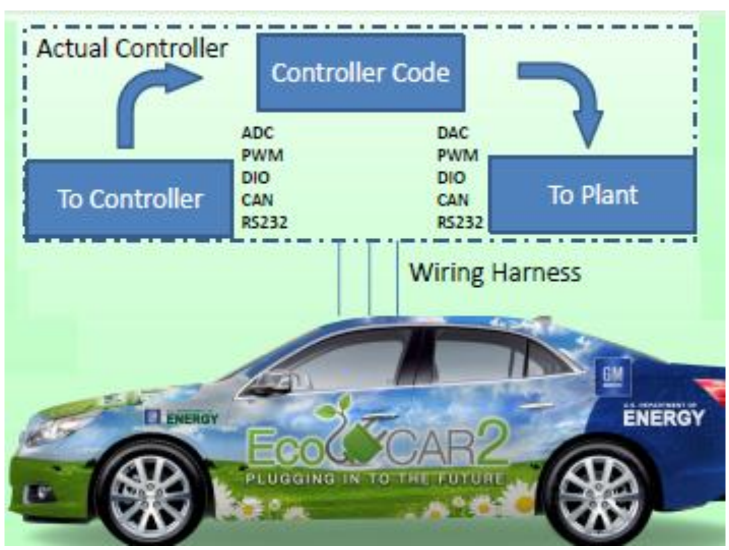


Figure 1-4. VIL (Vehicle-in-the-loop) Data Flow [9]

SIL is an important step in model-based design. Skipping SIL validation is impossible because testing based solely on HIL and physical prototypes would have only limited applicability. Some reactions of supervisory controller to certain faults can be investigated only in a SIL simulated environment due to safety hazards or costs of physical components' assembly. Additionally, HIL facilities are typically limited and expensive resources, whereas SIL-based testing can be completed with just a PC. SIL does not require that the plant be simulated in real-time so it can run many times faster than real-time simulation, allowing comprehensive logic tests, debugging and improvements that produce fast results. Therefore SIL is viewed as a HIL complement because it does not have the same limits as HIL testing nor as its replacement. Having a thorough and complete SIL design and validation is a valuable addition and contribution to minimize finding design errors during HIL and VIL testing which are more expensive and time consuming to diagnose [11]. Hence, the validation and testing of the supervisory controller's algorithms for SIL phases must be completed before testing the Hybrid Controller Unit (HCU) code in HIL and VIL.

1.3 Objective and Thesis Outline

The Hybrid Warriors of Wayne State University is participating in the 2011-2014 EcoCAR2 competition which focuses on designing a hybrid vehicle that maximizes efficiency and performance while minimizing emissions and petroleum usage. An operational supervisory controller for the team's hybrid architecture is designed to meet all safety and functional requirements while reducing fuel consumption. Also, the supervisory controller is organized and designed to be able to transition easily to HIL testing environment.

First, the control system architecture and requirements is defined and developed according to the interactions between the control units and Design Failure Mode and Effects Analysis (DFMEA) results. Next, the control strategies for the supervisory controller are presented. An operational supervisory controller is developed, verified and validated by SIL testing. The resulting algorithms (both supervisory controller and vehicle plant model) are prepared for HIL testing. Finally, the SIL results prove that the supervisory controller meets all the safety and functional requirements to reduce fuel consumption.

1.4 Base Conditions and Assumptions

Some initial conditions and assumptions were made for the development of the overall control strategy for the plug-in parallel-through-the-road (PTTR) HEV to clarify the coverage limit of this thesis. The control strategy will not address cold start operation and does not considered the effects of temperature in any model components. No emissions data was given in the initialization files so the models cannot calculate total emissions and therefore cannot be compared to real world data or vehicle technical specifications (VTS) [12].

CHAPTER 2. BACKGROUND AND METHODOLOGY

2.1 EcoCAR2 Competition

EcoCAR2 is a three-year student engineering competition sponsored by the U.S. Department of Energy and General Motors (GM). It challenges 15 universities across North America to re-engineer a Chevrolet Malibu without compromising performance, safety and consumer acceptability while reducing its environmental impact. The teams follow GM's vehicle development process generally for the engineering process of designing, building and refining their vehicle. The overall competition's goals focus on reducing fuel consumption, well-to-wheel greenhouse gas emissions, reduce criteria tailpipe emissions and maintain consumer acceptability in the areas of performance, utility and safety. Therefore, the competition focuses mostly on petroleum energy reduction because that is a benefit that a consumer can directly see. While lowering emissions is important, the benefit is not as obvious as the direct financial impact a consumer will see from petroleum energy reduction [13].

The first year of competition involves using computer simulation tools to design each team's vehicle, ending with a week-long competition where teams presented their work that they had completed during the year. The second year required the teams to integrate their own powertrain components into the Malibu safely and functioning properly. The year ends in final vehicle design in which the completed vehicle should be functioning properly. The third and final year is refinement where the vehicle is refined to a 99% production ready vehicle, ending with the vehicle testing complete event.

WSU Hybrid Warriors controls team is divided into different groups (G1, G2 and G3) to improve its probability of meeting the design requirements as seen in Table 2-1.

Table 2-1. WSU Controls Team Sub-groups

Controls Sub-group	Responsibilities
G1	The base of all our controls work will be done here, preparing and improving the high fidelity plant models to be used in SIL and HIL testing. Every new controls member and beginner level member will start here.
G2	Develop control algorithms and test using the plant model. Supply controller block updates to MIL/SIL group.
G3	Integrate SIL into HIL model and HIL test the control code. Vehicle level testing.

This creates and ensures that all Controls team members develop necessary proficiency (knowledge and hands-on experience) needed for actual control and/or controls testing. Additionally, this guarantees that the team performs all the necessary simulation testing and validation (MIL, SIL, and HIL) before moving to actual vehicle testing. This research focuses on the theoretical developments and works that have been performed to enable using SIL for the team's supervisory controller validation, so this thesis highlights and explains G1 and G2 works.

Within the Controls team, this author's roles and responsibilities consisted of directing, overseeing and updating G1 and G2 tasks. Most Controls team members are beginning level members so they spent most of their time under this author's direction helping with the simpler and repetitive parts of coding such as generating coverage reports for plant models that the author had updated. A selected few veteran members contributed some limited segments of code per discussions, directions and needs set up by this author. Overall, this author has designed the entire supervisory controller and done most of the coding including updating the plant models to meet the author's requirements, performed code integration and debugged all the works presented in this thesis.

2.2 Literature Review

Bayindir, Gozukucuk and Teke [14] have provided an overview of HEVs focusing on hybrid configurations and energy management strategies. The article starts with identifying the major characteristics of three different electric vehicles: battery operated vehicles (BEV), hybrid electric vehicle (HEV) and hydrogen fuel cell electric vehicle (FCEV). BEV is primarily suitable for small electric vehicles for short range and low speed community transportation. It uses only the electric machine for propulsion and requires to be recharged by electric grid charging facilities. HEV utilizes both electric machine and internal combustion engine to provide vehicle propulsion. This allows HEV to have longer driving ranges along with a better fuel economy as compared to internal combustion engine (ICE) vehicles. FCEV is still in early development stages; however it has long term potential for future main stream vehicles due to its zero emissions and high energy efficiency.

The article also focuses on evaluating the three different types of HEV powertrain configurations: Series, Parallel and combination (Series-parallel). The Series has no mechanical connections between ICE and wheels. All mechanical energy from the ICE is converted to electrical energy by a generator to power the electric motor to run the wheels and replenish the energy system. In Parallel, the mechanical power output and electrical power output are linked in parallel to drive the transmission. The ICE is generally turn on and operates at an almost constant power output. The electric motor assists the ICE at higher loads and acts as a generator in lower loads to capture the extra power from the ICE. The combination architecture displays features of both series and parallel hybrid configurations. Its powertrain configuration can vary depending on other factors that are not within the scope of this article but it is usually conjugate with power split devices that allows for power path from ICE to wheels.

Aside from powertrain configuration, the HEV overall design aims to get the most effective results with controlling conversion of energy on the powertrain. The authors presented four goals that can be achieved by an effective controls strategy: maximum fuel economy, minimum emissions, minimum system cost and good driving performance. It also states that energy management control strategies can be divided into two main areas, rule based and optimization based. Ruled based control strategy uses pre-determined rules and values to achieve best results for a specific drive cycle, whereas the optimization based control strategy focuses on minimizing cost functions which requires significant amount of computational work to obtain its global optimal solution. This article does not actually go into detailed control architecture or strategy but provides a concrete overview of HEV.

An IEEE article [15] by Wirasingha and Emadi has presented a review of control strategies for plug-in hybrid electric vehicles (PHEV). The PHEV modes of operation can provide the energy for propulsion using the engine or electric machine, or the two sources in combination with each other. State of charge levels of the energy storage system (ESS) decides which mode of operation is selected, charge depletion (CD) or charge sustaining (CS) mode. In CD mode, the vehicle is operated primarily by using the energy supplied from the electric propulsion machine. The ICE power is activated when the electric machine is not able to meet the power demand or the battery state of charge (SOC) drops too low. In CS mode, the vehicle propulsion can be powered by electric machine alone or engine alone or both to sustain SOC. Furthermore a PHEV has the advantage of improving the engine efficiency and fuel economy by using the electric machine during transient power demands and initial vehicle startup, and incorporating engine idle stops.

This article also divided the PHEV controllers into the same two groups: rule-based and optimization-based, but presented more details on each group. Rule-based control strategies optimize the performance of each component individually. Two types of rule-based control strategies were presented, deterministic rule-based methods and fuzzy-rule based controller. Deterministic rule-based controllers operate on a set of defined rules that are implemented before any actual operation. Its decision-making process is influenced by the operating conditions, instantaneous inputs, flowcharts and control parameter tables. Fuzzy logic controllers decrease computational burden and give a higher level of abstraction even though they are still based on predetermined rules. It is ideal for nonlinear time-varying systems such as a PHEV drivetrain because fuzzy logic is robust, adaptable to variations and easily adjustable. On the other hand, the optimization-based controllers optimize the vehicle as a whole, resulting in a global control solution. Optimization has the capability to integrate two variables, i.e., mileage and emissions goals as a cost function that can be optimized. This group is farther analyzed in this article by presenting two types of optimization-based controllers, global optimization and real-time optimization. Global optimization controllers are acausal systems that use historical data to define its cost function while minimizing it offline based on future expectations and results. Therefore the systems minimize the cost functions by using past and future variables/inputs of the drivetrain. Real-time optimization controllers are casual systems that have the ability to adapt in real time. These controllers attempt to optimize a cost function that was developed using past information. It strives to be adaptive controllers that can understand the average behavior of the respective driver while optimizing themselves for these situations. The article then goes on to describe particular examples of existing PHEV controllers of the two groups mentioned.

A SAE article [16] by Gonder and Markel starts by reviewing the main advantages of PHEV. The hybridization benefits of HEV can also be incorporated in PHEV, but it has the potential to reduce fuel consumption levels even more. In PHEV, some of the vehicle's usable energy in the form of electricity through a charging plug will displace some energy that is usually provided by burning fuel in HEV. The paper then goes on to compare three energy management approaches for the charge depletion (CD) operating period for plug-in hybrid electric vehicles: all electric-range strategy (AER), an engine-dominant blended strategy, and an electric-dominant blended strategy.

AER operates the PHEV electrically without assistance from the engine during CD operation. Principally, the motor satisfy the entire vehicle power demand and the engine remains off. The ability of the AER strategy to achieve all-electric CD operation requires the motor and energy storage system (ESS) power capability to at least match the maximum power requirement of the expected cycle. An AER PHEV driving more aggressively than the expected drive cycle can fail to meet the higher-power road load demand. The suggested solutions to prevent this is to design the all-electric operation on more aggressive driving cycles such as the Environmental Protection Agency (EPA) US06 cycle or allow engine assistance during CD operation. Furthermore, driving distance influenced the relative amount of petroleum displacement; hence the AER strategy provides maximum petroleum displacement for driving distances equal or less than the all-electric CD operation range.

An engine-dominant blended strategy uses the stored electrical charging energy to supplement engine operation. The vehicle may operate all-electrically during initial CD operation but the engine will turn on as soon as the driving demand becomes higher than the power capability of the motor and battery. The electrical system provides the extra power to allow the engine to operate in its efficient operating region while meeting the high drive power demands. Overall, the strategy maximizes the engine operating efficiency. The engine-dominant blended strategy uses the engine power earlier and more frequently as compared to the AER strategy, but the amount of petroleum savings will depend significantly on the driving distances between vehicle recharges. Fuel consumed during CS HEV operation is divided into the full CD plus CS distance to calculate average petroleum. Therefore, substantial fuel savings can be achieved in longer driving distances since the engine is operated mainly in its efficient area in both CD and CS distances. If the vehicle drives less than the CD distance, the vehicle under-utilizes the electrical energy resulting in more fuel consumption. The fuel consumption for under-utilizing the ESS will likely be greater than the additional savings from operating the engine in its efficient region and assisting the engine with electrical energy. Ultimately, the engine-dominant blended strategy is less than ideal if the vehicle driving distance is uncertain.

An electric-dominant blended strategy uses the engine power to assist the electric motor and battery operation. The vehicle operates all-electrically only until the driving demands surpass the power capability of the ESS and electric motor which resulted in turning on the engine to satisfy the transient load demands. The engine may not be operated at its maximum efficiency point but still may result in small fuel consumption because of the small loads assistances that it is providing. The CD distance for the electric-dominant blended strategy will be greater than that for the AER strategy and less than that for the engine-dominant blended strategy. However, the percentage savings will be diluted for longer distances as more miles of CS HEV operation become included, similarly to the AER strategy. The electric-dominant blended strategy will use more fuel ultimately due to focusing less on maximizing engine efficiency when compared to the engine-dominant blended strategy for driving pass the longest

CD distance (engine-dominant blended). However, for driving much less than the longest CD distance, the electric-dominant blended strategy will consume significantly less fuel due to its greater utilization of electrical recharge energy.

2.3 WSU Selected Hybrid Architecture

Although the detailed WSU hybrid architecture selection is not within the scope of this thesis, a brief summary discussing the architecture selection approach is helpful in understanding the goals required by the competition. Initially, the team investigated three different hybrid architectures: series, pre-transmission parallel, and plug-in parallel-through-the-road (PTTR). The final decision between the three architectures was based on the following design constraints: performance and energy consumption, packaging, customer acceptability, controls complexity, resource and experience. Performance and energy consumption were taken from modeling and simulation using EcoCAR2-sponsored Autonomie. The packaging involving the mass and weight distribution limits and the expected complexity of the different architectures' installations were discussed. Customer acceptability is based on how changes made to the vehicle's architecture would affect the customer's perception of the vehicle. The controls complexity considers the required resources and learning curve to reach 99% buyoff based on the Vehicle Development Process within the competition timeline. The team's resources and experience were considered based on cost, estimated lead times, availability of special facilities, and the usefulness of members and faculty past experiences with each architecture or components of that hybrid architecture. The design constraints were separated into each criterion and assigned a weight factor based on its importance to the team. The overall scoring is the sum of all weighted criterion for each of the architecture as seen in Table 2-2. Plug-in PTTR is the team's chosen architecture based on highest overall scoring.

The 2013 Chevy Malibu is the base vehicle for the plug-in PTTR. Some of the base components and control modules will be kept while new ones will be added. Plug-in PTTR has a complete separation between the rear wheel drivetrain (RWD) high-voltage (HV) bus components and the front wheel drivetrain (FWD) as seen in Figure 2-1. The engine clutch of the base vehicle is removed. The transmission still retains the torque converter. A differential and axle are added on the rear of the vehicle [12]. The sizes and characteristics of the new drivetrain components are summarized in Appendix A. The MicroAutoBox II (MABXII) is the Hybrid Controller Unit (HCU) so the final supervisory controller code will be uploaded to it.

Table 2-2. Architecture Selection Matrix [13]

Criteria	Weight	Architecture 1 – EREV	Architecture 2 – Plug-in Parallel through the road	Architecture 3 – Pre-Transmission Parallel
Team's Resources (Time, Money, Facilities)	5	2	3	1
WTW PEU (with E85 Fuel)	4	1	2	3
Packaging	4	2	3	2
Team's Experience	4	3	2	1
Performance (Acceleration & Gradeability)	3	1	3	3
Controls Complexity	2	2	3	1
Customer Acceptability	1	1	3	2
Scoring	-	41	63	42

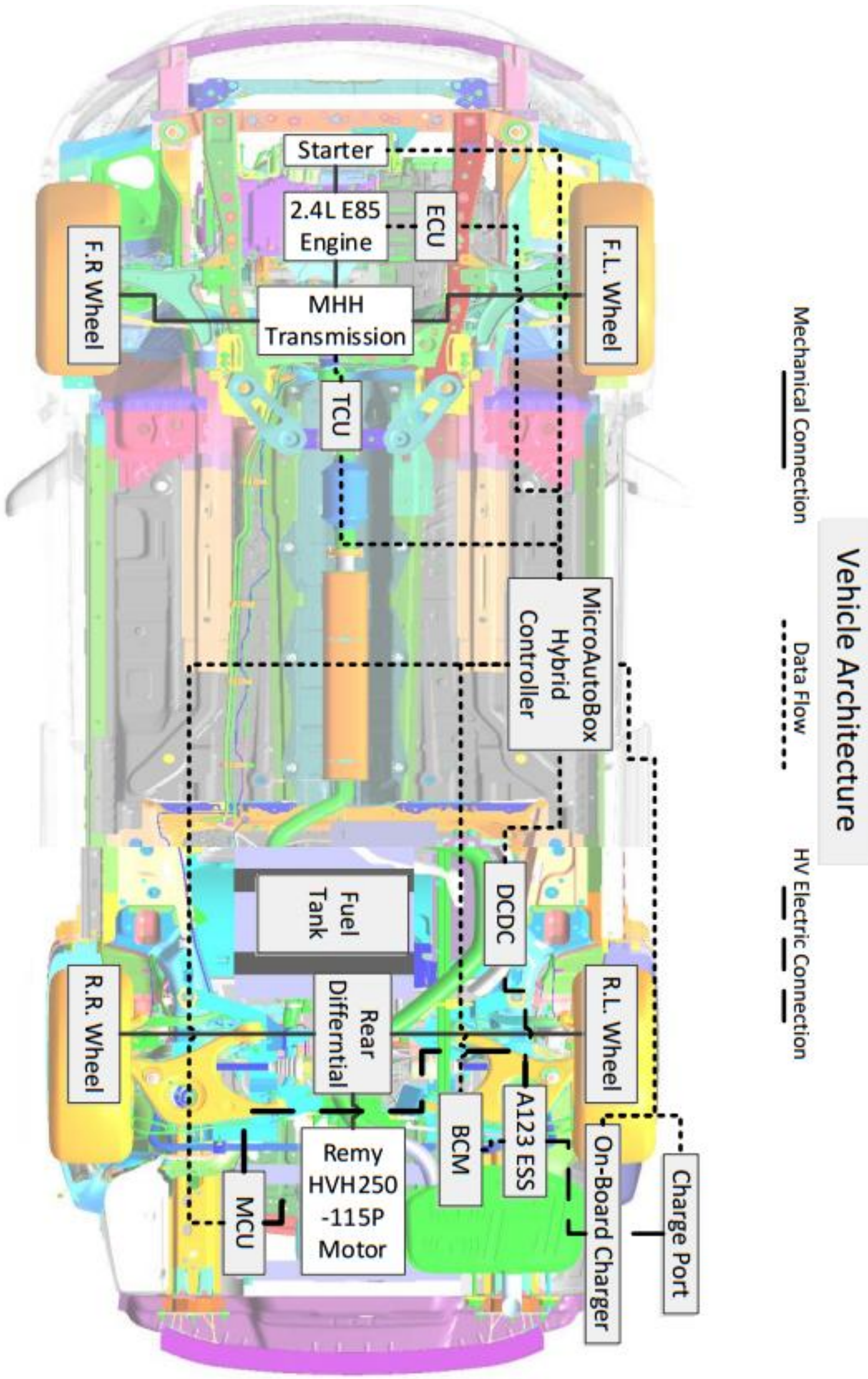


Figure 2-1. Vehicle architecture basic schematic [17]

2.4 DFMEA

The team understands that their vehicle design process needs to include DFMEAs before hardware is built and continues during the vehicle development process. Generally, DFMEA is an established reliability engineering activity that creates fault tolerant design, testability, safety and related functions. The main intention of developing DFMEAs is to identify potential failure modes and the corrective actions that can be taken to remove or continually reduce the potential for occurrence. The main steps in developing DFMEAs are to assume that failure could occur and not necessarily will occur, identify the effects of the failures in terms of what the customer would notice or experience and list all of the causes assignable to each failure mode. Then, the occurrence and detection probabilities are determined in combination with a severity criterion to calculate a risk priority number (RPN) for ranking corrective action consideration [18].

DFMEAs require the team to use past experience and engineering critical thinking to rate each of the potential risks or problems according to three rating scales:

- **Severity**, which rates the severity of the potential effect of the failure.
- **Occurrence**, which rates the likelihood that the failure will occur.
- **Detection**, which rates the likelihood that the problem will be detected before it reaches the end-user/customer.

The scales of detection, severity and occurrence stay consistent for the comparisons among designs to be valid and they range from 1 to 10, with a larger number representing higher seriousness or risk as seen in Table 2-3. From these rating scales, the RPN is calculated as:

$$\text{RPN} = \text{Severity} \times \text{Occurrence} \times \text{Detection}\ . \qquad (1)$$

The RPN value for each potential problem can then be used to compare the issues identified within the analysis [20].

While this thesis is focused on the supervisory controller, the DFMEAs developed are focused on the ECUs' failure modes that can affect the supervisory controller functions. Internal failure modes between main components and its own electronic controller units (e.g. engine and engine controller module) will not be considered unless it affects the supervisory controller. An example DFMEA can be seen in Table 2-4.

Table 2-3. Criteria for Severity-occurrence-detection Ratings [19]

Rating	Severity	Criteria	Detection
1	Not noticeable to customer.	Highly unlikely. <1 in 1.5 million opportunities.	Almost certain to detect failure.
2	Some customers will notice. Very minor effect on product or system.	Extremely rare. 1 in 150,000 opportunities.	Excellent chance of detecting failure: 99.99%
3	Most customers will notice. Minor effect on product or system.	Rare. 1 in 15,000 opportunities.	High chance of detecting failure: 99.9%
4	Customer slightly annoyed. Product or system slightly impaired.	Few. 1 out of 2000 opportunities.	Good chance of detecting failure: 95%
5	Customer annoyed. Noncritical aspects of product or system impaired.	Occasional. 1 out of 500 opportunities.	Fair chance of detecting failure: 80%
6	Customer experiences discomfort or inconvenience. Non critical elements of product or system inoperable.	Often. 1 out of 100 opportunities.	Might detect failure: 50%
7	Customer very dissatisfied. Partial failure of critical elements of product or system. Other systems are affected.	Frequent. 1 out of 100 opportunities.	Unlikely to detect failure: 20%
8	Customer highly dissatisfied. Product or system inoperable, but safe.	Repeated. 1 out of 100 opportunities.	Very unlikely to detect failure: 10%
9	Customer safety or regulatory compliance endangered, with warning.	Common. 1 out of 100 opportunities.	Highly unlikely to detect failure: 5%
10	Catastrophic. Customer safety or regulatory compliance endangered, without warning.	Almost certain. 1 out of 100 opportunities.	Nearly certain not to detect failure, or no controls in place

Table 2-4. DFMEA Example

Line No.	Item / Function of the Part	Potential Failure Mode (Loss of Function or value to customer)	Potential Effect(s) of Failure	SEV	Potential Cause(s) / Mechanism(s) of Failure	OCC	DET	RPN	Recommended Action(s)
1	Onboard charger	Stays on when should be off	Excess power to battery resulting in damage.	4	Defective charger or indicator that battery is full.	2	5	40	Needs overcharging protection such as cell voltage detection and SOC limits to close connectors when battery is full.

CHAPTER 3. SUPERVISORY CONTROLLER DEVELOPMENT

3.1 Supervisory Controller Initial Information

Although a conventional vehicle has no main ECU giving commands to other ECUs, hybrid vehicles require a supervisory controller to operate the various powertrain components. There are two levels of control actions in HEV: supervisory control and component control as seen in Figure 3-1. They both aim to minimize fuel consumption while considering performance and drivability. The supervisory control is responsible for interpreting the driver demand, responding to component level fault conditions reported by other ECUs, detecting system level fault conditions, determining modes of operation, and commanding powertrain components. The component control accepts commands from the supervisory controller and relay those commands to its related actuators and provides feedback information back to the supervisory controller for further analyses. Since this thesis focuses on the strategies for improving fuel economy and providing a functional HEV supervisory controller through SIL validation, emissions modeling and control will not be discussed [6].

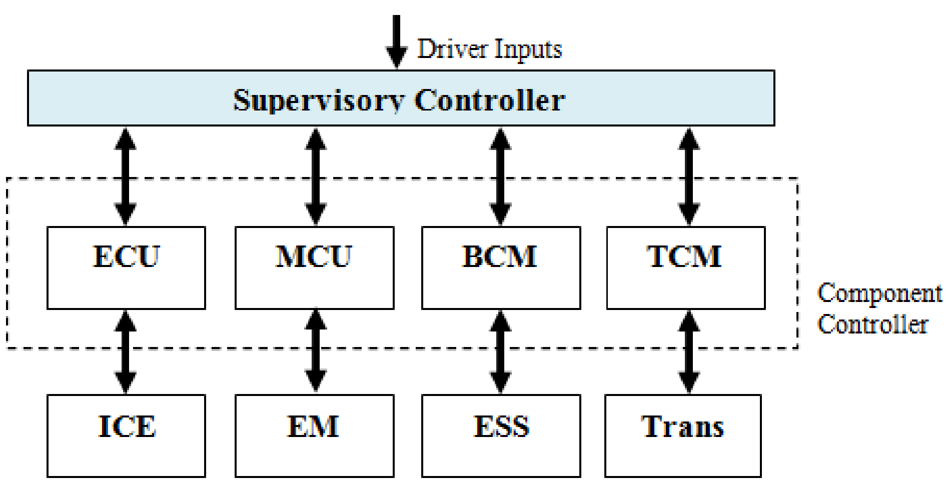


Figure 3-1. Hierarchical Control in HEV

The team is following the V-diagram development process customized to the team's capabilities and project's requirements to develop and validate its supervisor controller as shown in Figure 3-2. The blue texts are steps that were taken to complete MIL and SIL tests. It should be noted that MIL testing are the initial steps required for SIL testing. Therefore only SIL validation will be presented since its simulation results will be very similar or the same to the MIL results. The red texts are steps that will be taken to complete HIL tests. The green texts are the steps that are to be taken to perform VIL tests for each completed HIL-tested requirement.

The first step to supervisory controller development is to define the requirements of the controller. Each signal that the supervisory controller must read, interpret and output brings a set of requirements to be implemented. Functional requirements are determined from the vehicle's components and its ECUs because proper supervisory controller interactions with ECUs are crucial for successful vehicle functionality. Additionally, the complexity of the WSU's EcoCAR2 design makes safety one of the team's highest priorities. The supervisory controller needs to prevent safety hazards before they occur as well as react to hazards quickly and safely in the event that a component does become damaged or faulty while driving. The preventative measures can be identified from DFMEAs.

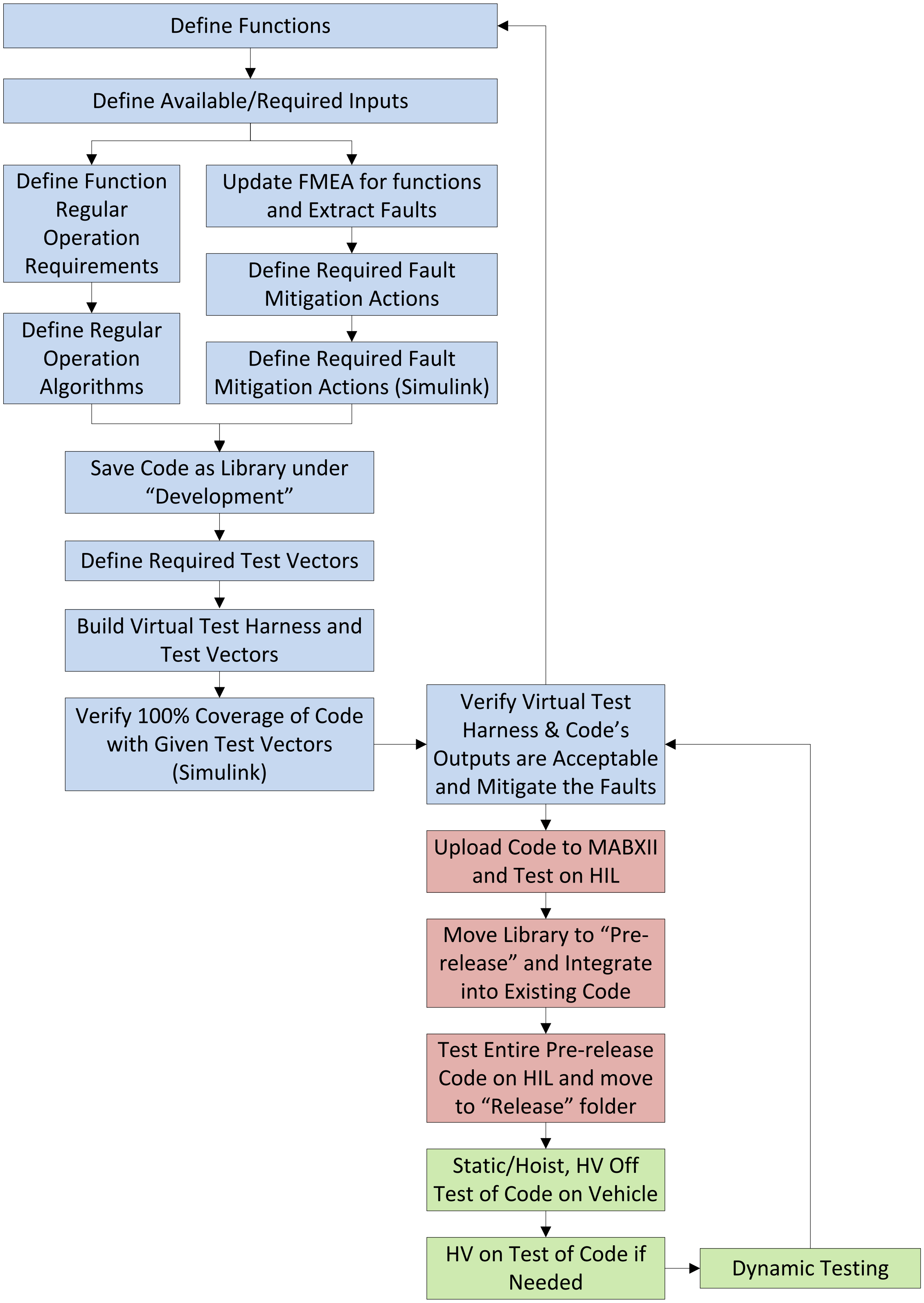


Figure 3-2. V-diagram Controller Validation Flowchart

3.2 Vehicle Functionality Requirements

The actual ECUs that are implemented in the vehicle are sourced from other non-hybrid applications that are specific to their components not the vehicle as a whole. As a result, the functional requirements for the supervisory controller can be identified by the vehicle's components to understand the necessary communication between the two kinds of controllers (supervisory and component) for successful vehicle control. Table 3-1 summarizes the current supervisory controller's requirements for vehicle functionality as identified by service manuals and documentations of the hardware components and its ECUs. Figure 3-3 shows an example of this process between the supervisory controller and the component controller MCU, working from the HCU interaction with the MCU to the requirements identified.

Table 3-1. Components Controlled by HCU (Hybrid Controller Unit) [13]

System	Responsible for	Major supervisory controller control parameters required to control
ECM	Proper engine and fuel system operation.	Enable, torque, speed, starter, ignition, shutdown.
TCU	Proper transmission operation	Gear shift, auxiliary trans pump pressure.
MCU	Inverter and motor operation	Enable, direction, torque.
BCM	ESS operation	Enable, close/open contactors, calculates GFD, vehicle EPO.
APM	High voltage DC power from ESS to be converted to 12-13V	Enable, set low voltage threshold
OBC	Plug-in battery charging	Enable

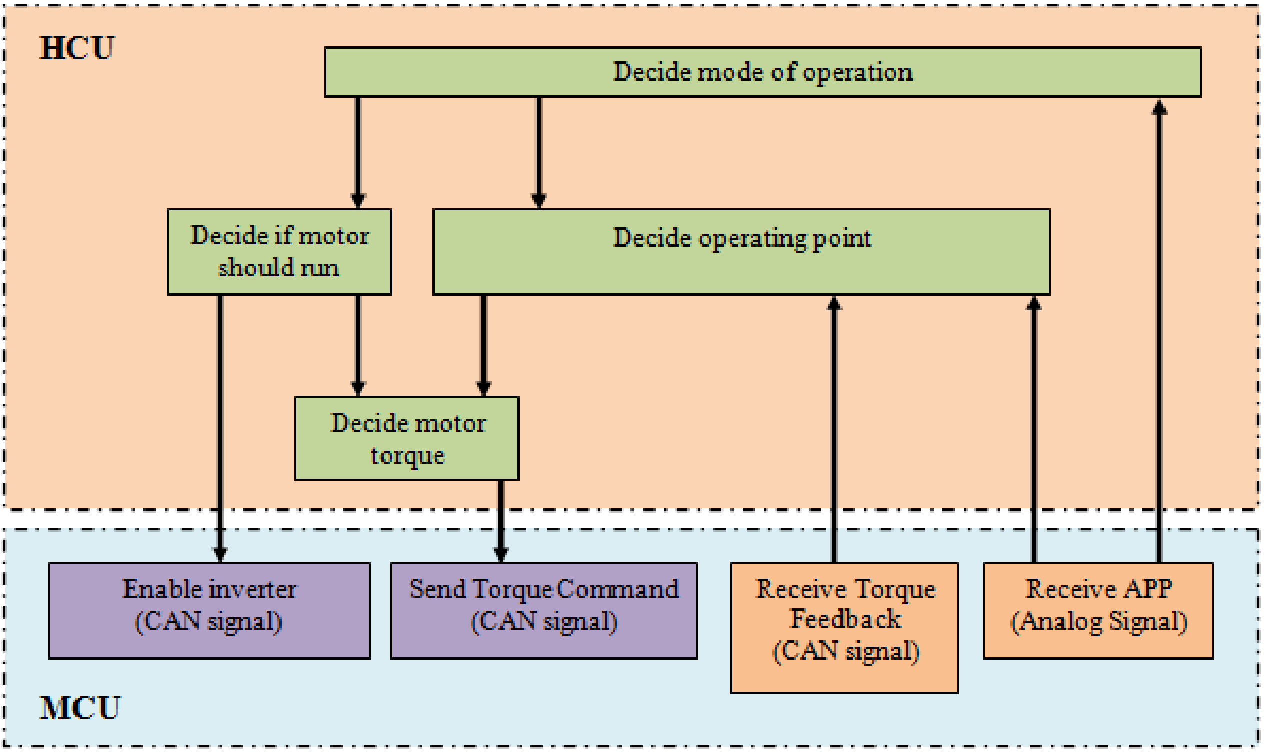


Figure 3-3. HCU Interaction with MCU

As a result, the infrastructure of the plant models and its soft ECUs are designed to be able to test the supervisory requirements. The focus of the vehicle model development is to simulate the minimum soft ECU characteristics needed to correspond with the actual vehicle integration timeline and be able to perform supervisory controller validation rapidly. All the signals from/to the supervisory controller that are required for its validation are incorporated.

3.3 Vehicle Model Development

The plant models inside the vehicle model are being developed in MATLAB Simulink to simulate some behavior of the components (ECM, TCM, ESS etc.) for supporting the virtual bench test in MIL and SIL. The base vehicle model was created by the Hybrid Warriors' team leader Idan Regev. Then it was updated to correlate with the supervisory controller covered in this thesis.

First, test benches using signal builders are built by this author collaborating with the Controls team and used to test the plant models and soft ECUs inside the vehicle model. In Simulink, the Signal Builder blocks incorporate test cases as signal sources in the models as seen in Figure 3-4 displaying the transmission plant model virtual test bench or known as MIL testing. Figure 3-5 shows a part of the Signal Builder with different groups of signals for bench testing the transmission plant model. These test cases are used to see if the plant model is running as expected.

The types of interactions between the driver, HCU (Hybrid Controller Unit) and ECUs (Engine Control Units) are analyzed. As seen earlier in Table 3-1, the controllers' interaction for all important powertrain and chassis control systems is summarized and presented. This table along with the vehicle communication architecture as seen in Figure 3-7 is the basis of determining the data flows that the vehicle model should consist between the HCU and ECUs. Therefore the interactions between the vehicle model and the supervisory controller model follow the same communication architecture as implemented in the actual vehicle [13].

The vehicle model can be seen in Figure 3-6. The MAT files given by –EcoCAR2 were used to supply the required data for this model.

Overall, the vehicle model contains soft ECUs that control a series of actuators in its corresponding plant models to ensure optimum operation that resembles its hardware counterparts. This is done by reading values from a multitude of sensors, interpreting the data using multidimensional performance maps (called look-up tables), and adjusting the actuators. The soft ECUs' signals duplicates the actual ECU's by staying within the actual values' ranges, being group into different types of signals (CAN, digital, analog, etc.) before transmitting or receiving and incorporating the same units.

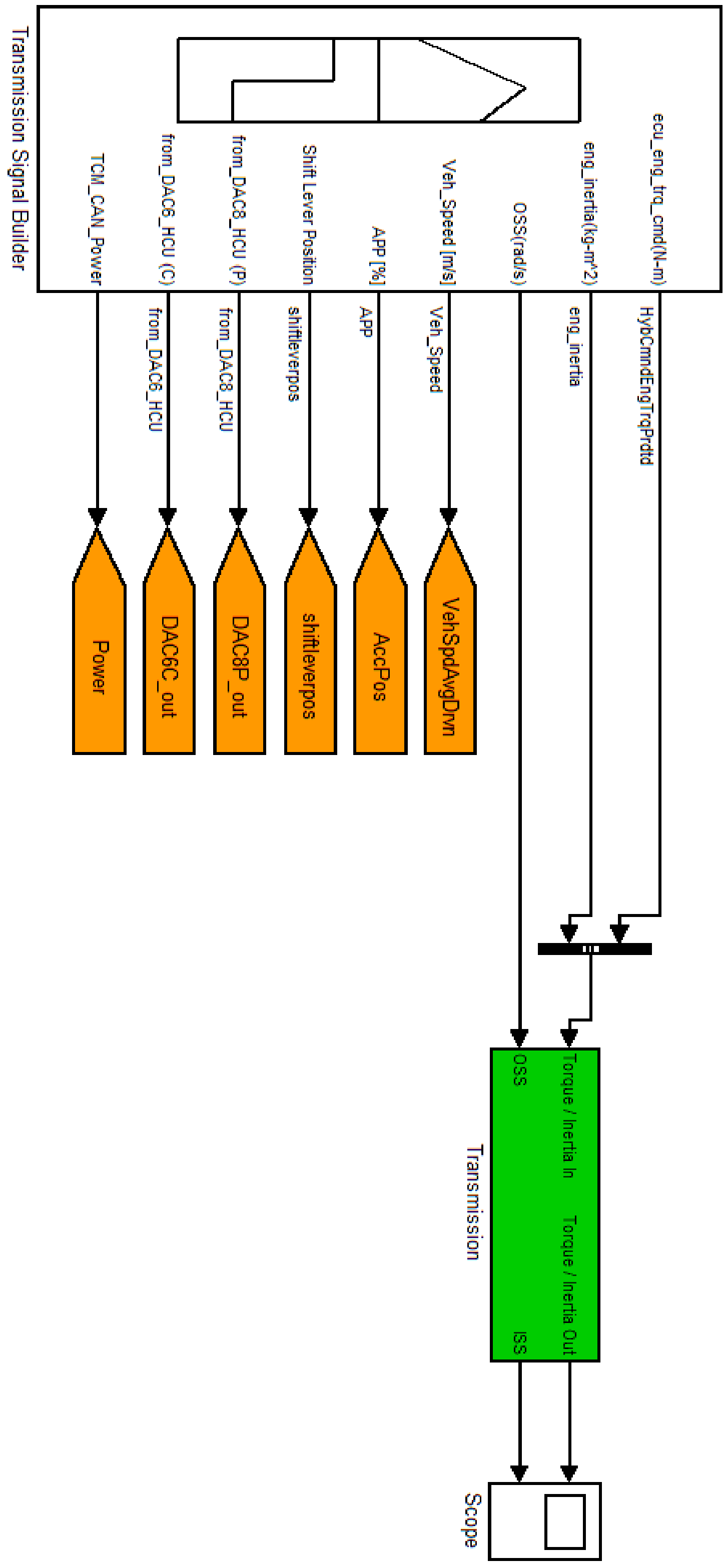


Figure 3-4. Transmission Plant Model Virtual Test Bench

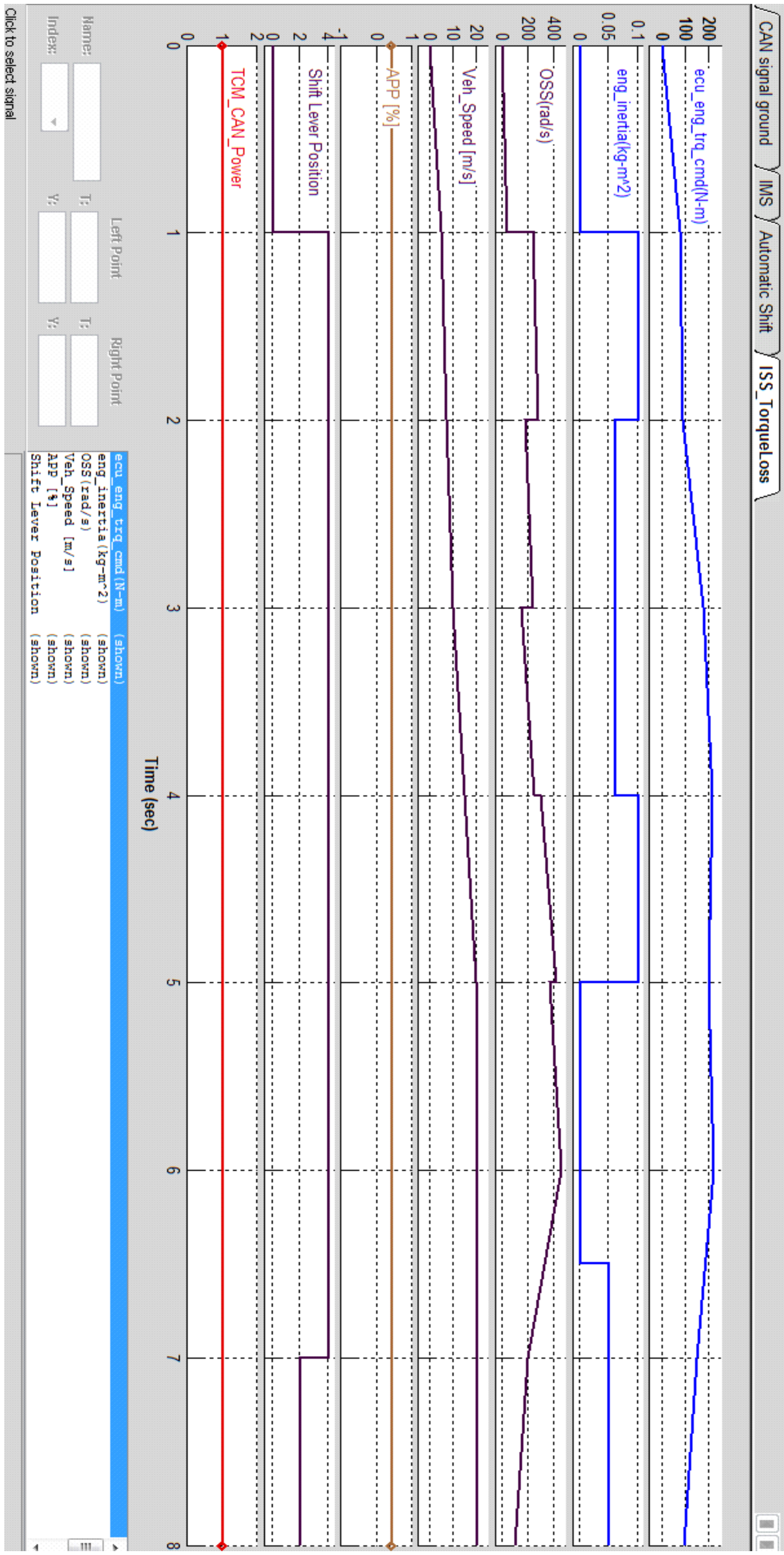


Figure 3-5. Transmission Test Cases inside Signal Builder

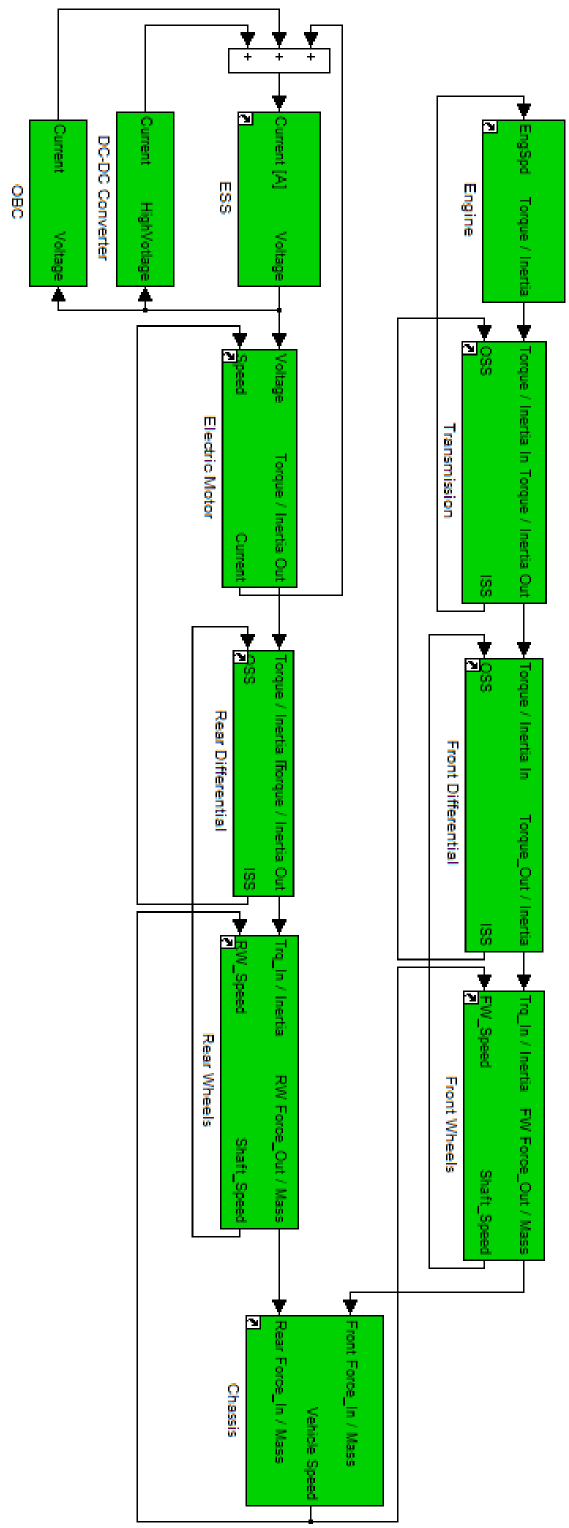


Figure 3-6. Vehicle Plant Model

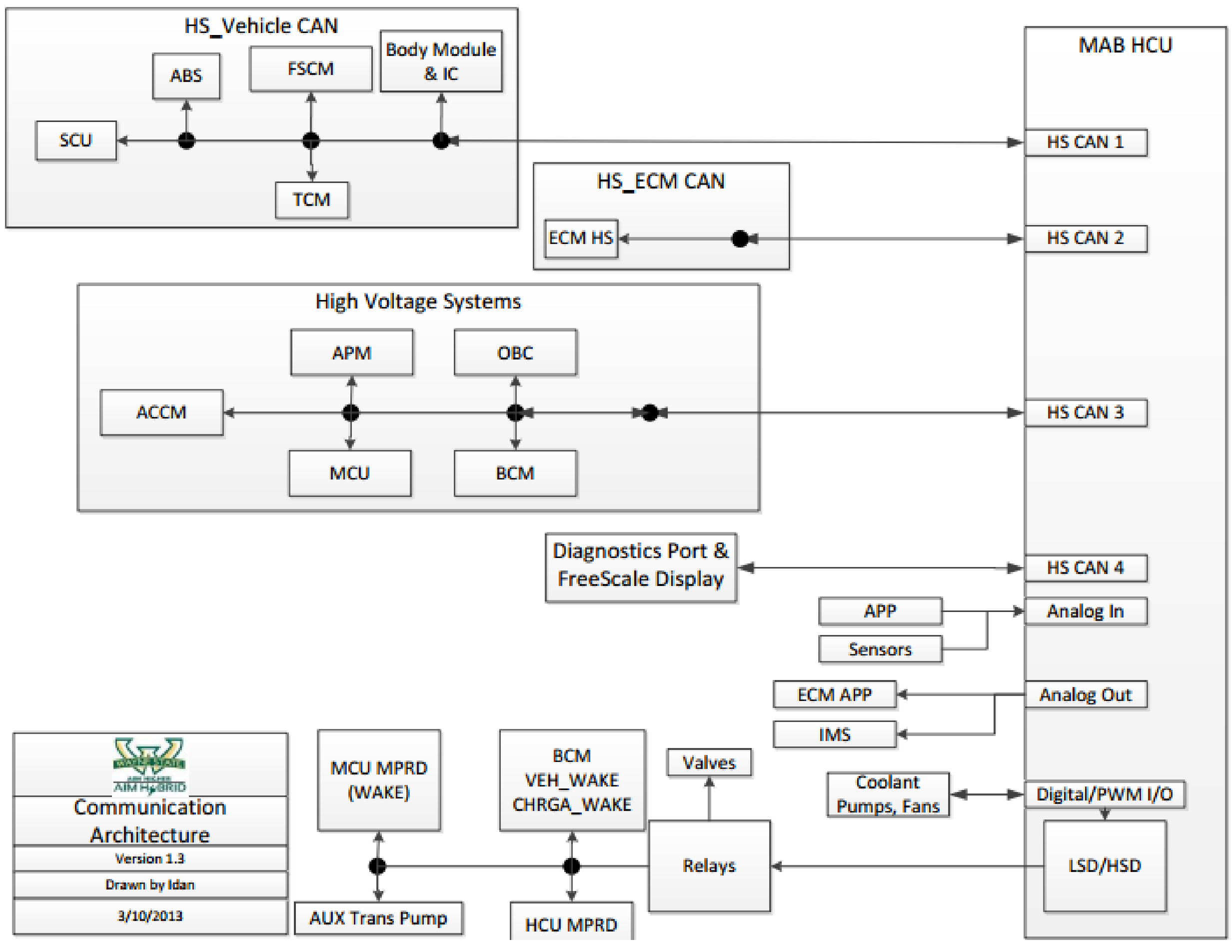


Figure 3-7. Communication Architecture [13]

A partial controller interaction diagram as seen in Figure 3-8 displays an example to further clarify the different types of interactions that occur in the team's vehicle. This example diagram details the interactions among the HCU, ECM, driver and engine. The driver (green - 1) presses the accelerator pedal which is converted as an analog signal (blue - 2) and passed to the HCU. All the actuators and sensors signals that the ECM controls or reads on the engine are analog interactions (blue - 2 & 3). HCU uses the analog signal to control ECM APP input to command engine torque (blue - 4). CAN interaction contains command signal (red - 1) that the HCU uses to start and shut off the engine, while the other return a CAN signal (red - 2) contains feedback signals such as engine speed and achieved engine torque [6]. A complete controller interaction diagram is shown in Appendix B.

In order to standardize the communication between different control units on the model, the soft ECUs' CAN signals were built and named accordingly to the GM CANdb network (DBC) files for the FWD hardware and the team's developed DBC files for RWD hardware. Since the focus of the thesis is the supervisory controller or referred to as HCU, the plant models and its soft ECUs were simplified in comparison to its more complex hardware counterparts. Only the characteristics that pertain to the validation and verification of the supervisory controller will be presented.

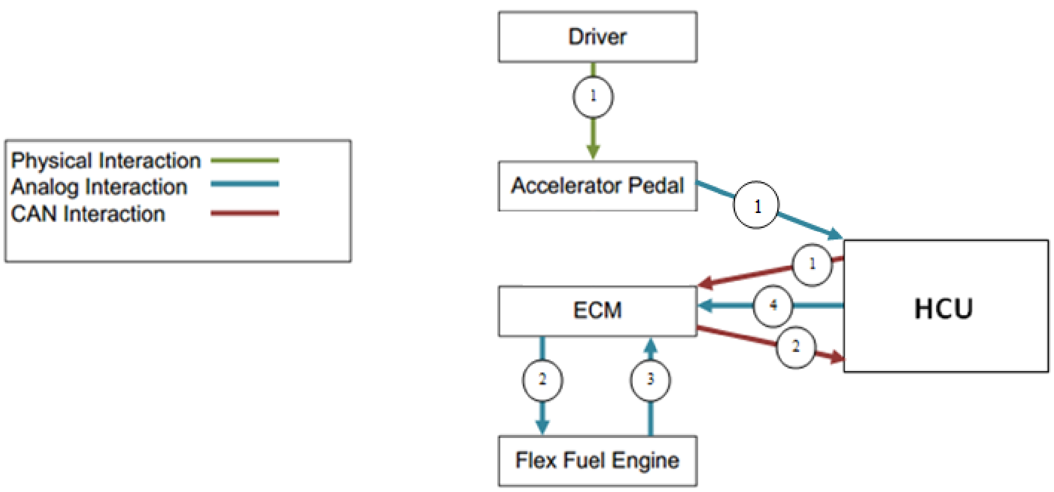


Figure 3-8. Partial Controller Interaction Diagram

3.3.1 Engine Plant Model

The engine plant model including the soft ECM simulates the LE9 engine with a maximum torque of 230 Nm at 5000 RPM. Performance and efficiency maps provided by EcoCAR2, such as the fuel consumption rate at a certain engine speed and torque were used. ECM receives the basic driver commands from the HCU. The key position cranks the actual engine so the HCU will simulate a key crank to start the engine. Engine torque is controlled by the accelerator pedal in the actual ECM. Therefore HCU will need to send a recast or modified APP signal to the ECM to command engine torque as seen in Figure 3-9.

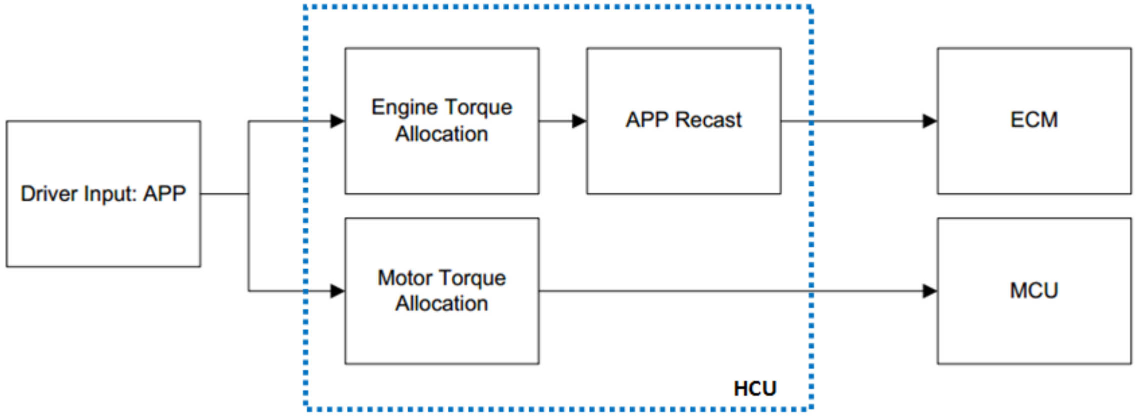


Figure 3-9. APP (Accelerator Pedal Position) Recast

3.3.2 Transmission Plant Model

The transmission plant model including the soft TCM calculates the transmission output torque and its torque loss due to the gear efficiencies. It also contains the IMS block emulating the actual IMS hardware. Input shaft speed is calculated based on output shaft speed and gear ratio. The accelerator pedal position and current gear position are indexed to determine the optimum vehicle speed which is then matched with the current vehicle speed to determine if gear shift is needed or not.

The actual IMS is a sensor that translates the rotational motion of the manual shaft that is connected to the PRNDL into electrical signals that are read by the TCM. The electrical signals represent a shift lever position. Therefore an IMS model is included in the transmission plant model which consists of a truth table mapping from the shift lever position: park, reverse, neutral, drive, and manual according to the analog outputs: A, B, C, P, and P/N based on IMS specifications as seen in Table 3-2 [21].

Table 3-2. IMS (Internal Mode Switch) Bit Logic for Shift Lever Position

IMS Grey Code Bit Logic					
Shift Lever Position	IMS A	IMS B	IMS C	IMS P	ECM P/N
Park	Grounded	Open	Open	Grounded	Grounded
Reverse	Grounded	Grounded	Open	Open	Open
Neutral	Open	Grounded	Open	Grounded	Grounded
Drive	Open	Grounded	Grounded	Open	Open
Manual	Grounded	Grounded	Grounded	Grounded	Open

The IMS model is implemented because the HCU needs to fake some of the signals that the TCM expects to be able to command Neutral while driving with the RWD. This is possible by opening IMS circuit C and grounding IMS circuit P. Also the automatic gear shifting is allowed only if the shift lever position output from IMS logic is set to drive.

3.3.3 Energy Storage System (ESS) Plant Model

The ESS plant model simulates the electrical properties of the ESS while the soft BCM (Battery Control Module) performs the calculations. BCM monitors the ESS and controls the contactors. ESS is discharged when the motor is providing power to the vehicle and charged when power is regenerating through motor to the battery or by the on-board charger. The battery voltage and resistance were configured by 2D-lookup maps with SOC level as the input. The temperature of the battery cells are set to the normal temperature of an operating ESS which is 25 degrees since the thermal effects are not implemented in this thesis.

The buffer calculation will need to be included in this plant model. It is A123's way of letting the user know when the current is getting close to be "cut off". When the buffer hits 0 or 100 the peak current limit is reduced by 100A/sec down to the continuous positive or negative value. At any point that the battery is drawn more than that limit, the BCM will open contactors and HV (High Voltage) will be shut off immediately. 100A/sec is equivalent to approximately 100Nm/sec so if the vehicle is in the middle of accelerating at 360Nm, it will lose half of its torque in less than 2 seconds. To prevent an accident HCU is responsible for ensuring that the buffer never hits 0 during discharging or 100 during charging [22].

Additionally, the battery operation with regards to its state of charge (SOC) and power requested will be briefly discussed. SOC is defined as the ratio of the instantaneous charge stored in the battery to its maximum charge capacity. It can be expressed as:

$$\text{SOC} = \frac{\text{Instantaneous Capacity}}{\text{Maximum Capacity}} \times 100 \,. \tag{2}$$

The instantaneous capacity is define as Equation (3), where Q_0 is the initial capacity and I is the accumulative current:

$$\text{InstantaneousCapacity} = Q_0 - \int \text{Idt} \,. \tag{3}$$

If the value of I is negative, battery regenerating occurred and the Instantaneous Capacity increases which increases the SOC level. If the value of I is positive, battery depleting occurred so the Instantaneous Capacity decreases which decreases the SOC level [23].

3.3.4 Electric Motor Plant Model

The electric motor plant model is modeled after the Remy motor with 400Nm peak torque. The motor provides the demanded torque by using the energy provided by the battery. The efficiency map of this Remy model as seen in Figure 3-10 is indexed by the shaft speed (in RPM) and the torque range (in Nm). The sign of the motor torque indicates the motor's direction. Positive torque means the traction motor is providing power to propel the vehicle. Negative torque occurs when the motor is acting as a generator restoring energy to the battery by regeneration. The HCU enables the inverter to start the motor, and it determines the direction of the motor, forward or reverse by transmitting positive or negative torque requests [23].

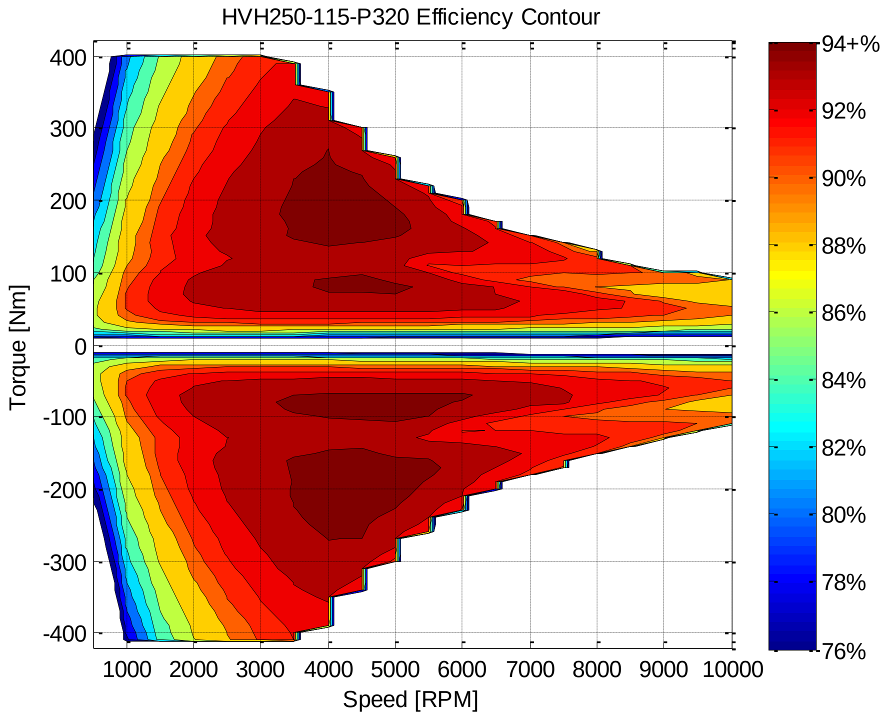


Figure 3-10. Efficiency Map Used for the Electric Motor Plant Model [24]

3.3.5 Front and Rear Differential Plant Models

The purpose of the front and rear differential models is to simulate the behavior of the separate differentials on the plug-in PTTR. It receives torque and inertia from the transmission or electric motor as inputs. The output torque from both the front and rear differential models can be calculated by the following equation:

$$T_D = T_I \times E_D \times R_D \,, \tag{4}$$

where T_D is the differential torque, T_I is the input torque from the transmission or electric motor, E_D is the differential efficiency, and R_D is the differential ratio. The output inertia, I_O from the differential models is calculated by:

$$I_O = \left(I_I \times {R_D}^2\right) + I_{F,R} \,, \tag{5}$$

where I_I is the input inertia from the transmission or electric motor, R_D is the differential ratio and $I_{F,R}$ is the front or rear differential inertia [25].

3.3.6 Front and Rear Wheels Plant Models

The front and rear wheels' block calculate the front and rear wheel forces, masses and shaft speeds by taking into consideration the wheels' inertia, positive torque commands, front braking torque command, rear negative torque command, and the wheels' radii as seen in Equations (6) and (7):

$$F_W = \frac{T_D}{R_W}, \tag{6}$$

where F_W is the wheel force, T_D is the differential torque and R_W is the wheel radius.

$$M_W = I_D + 2 \times I_W \times {\frac{1}{R_W}}^{2}, \tag{7}$$

where M_W is the wheel mass, I_D is differential inertia, I_W is the wheel inertia and R_W is the wheel radius. The shaft speed ω_S is calculated by Equation (8):

$$\omega_S = \frac{\omega_W}{R_W}, \tag{8}$$

where ω_S is the shaft speed, ω_W is the wheel speed and R_W is the wheel radius.

3.3.7 Chassis Plant Model

The chassis plant model containing the body control module (BodyCM) and electronic brake control module (EBCM) calculates the instantaneous vehicle speed by:

$$\text{Instantaneous Vehicle Speed} = \frac{F_{TW} - R_L}{M_{TW} + M_V} \times \Delta t + v_o, \tag{9}$$

where F_{TW} is the total wheel force (front and rear wheel forces), R_L is the road load, Δt is the step size and v_o is the previous vehicle speed.

Also a wheel slip algorithm will need to be implemented since the front and rear wheels are being driven by two different powertrains. Ineffective FWD and RWD torque coordination can result in the wheels slipping that can detriment vehicle performance and passenger safety. Therefore the supervisory controller will need to detect the wheels slipping early and reduce torque as necessary to prevent extensive slipping before it causes an ABS event. It is best to avoid using the ABS to allow safe regeneration and preventing slip conditions that are bad for the tires and vehicle stability [26].

The tire traction force F_t is given by Equation (10):

$$F_t = \mu(\lambda) \times F_N , \tag{10}$$

where F_N is the normal tire force and $\mu(\lambda)$ is the dry asphalt and concrete friction coefficient of 0.9. Rear wheels are slipping when the rear wheel force is greater than the rear tire traction force. Similarly, the front wheels are slipping when the front wheel force is greater than the front tire traction force.

3.3.8 DC-DC Converter Plant Model

The DC-DC converter plant model converts the high voltage from the battery to 12 VDC to run the vehicle's low voltage systems. The accessory loads are estimated at 720 W and the breakdown is given in Table 3-3. The total accessory does not include any air conditioning, since A/C is not included in the EcoCAR2 testing requirements. A/C would have added 4-6 kW (peak) of additional accessory load for real world fuel economy [27].

Table 3-3. Accessory Loads [10]

Wattage	**Accessory Loads**
150	Electric Power Steering (1000 W peak) [10]
150	Radiator Fan (800 W peak)
10	Exhaust Air Pump (300 W peak)
200	Ignition, Wipers, Lights, IP/Gage Cluster, Infotainment/GPS, Cabin Blower Fan, various ECUs (engine, transmission, body/chassis, brakes, etc.)
50	MicroAutoBox
25	Coolant pump for battery pack
25	Coolant pump for DC-DC converter, motor controller, motor
90	DC-DC converter losses - 86% efficiency for Vicor DC-DC Converter
20	BCM & Contactors
720	**Total Electrical accessory load for Hybrid**

3.3.9 On-Board Charger Plant Model

HCU detects when the on-board charger (OBC) is connected to the charge port and signals the OBC plant model to transmit its 3.3 kW. This wattage is converted to its current equivalent by Equation (11) and recharges the ESS:

$$I_{OBC} = \frac{P_{OBC}}{V_H}, \quad (11)$$

where I_{OBC} is the current from the OBC that recharges the ESS, the P_{OBC} is the OBC output power and V_H is the high voltage from the ESS.

All the other controllers that exist in the vehicle but were not mentioned will not be modeled. There is no need to model them because they are not involved in the current supervisory controller validation. A summary of the powertrain control units that are currently modeled in the vehicle plant model is seen in Table 3.4. If there are new requirements that are to be added, they will be used for developing other component models if needed. Specific algorithms that address each requirement (old or new) and the development/testing status of those algorithms will be maintained to ensure proper validation of the strategy.

Table 3-4. ECUs Implemented in Vehicle Model

Existing Control Units			
Component	ECU	Supplier	Functions
6-Speed Automatic Transmission	TCM	General Motors	Determines the transmission position; contains gear shift logic.
Vehicle Chassis	BodyCM	General Motors	Converts Driver to CAN signals that are transmitted by the BodyCM such as brake pedal position and key position.
Brake System	EBCM	General Motors	Senses when brake pedal position is pressed.
New Control Units			
Flex Fuel Engine	ECM	General Motors	Limits engine torque, calculates fuel consumption and engine efficiency.
Rear Traction Motor/Generator	MCU	Remy	Limits motor torque and calculates motor efficiency.
Energy Storage System	BCM	A123	Calculates SOC (%); Emulates HV status sequence for opening/closing contactors.
On-board Charger	OBC Controller	Brusa	Output 3.3 kW when charger is enabled.
DC-DC Converter	APM	General Motors	Converts high voltage from ESS to 12 V to power accessory loads.

CHAPTER 4. CONTROL STRATEGY DEVELOPMENT

4.1 Software Organization

It is important to develop the control strategy in a way that supports readability and understandability. Since the competition timeline is three years, the learning curves for new members must be minimized as much as possible to sustain a competitive team when for example veteran team members graduate the project. This is addressed by utilizing Simulink, a visual based programming language since it promotes readability of code and minimizes syntax errors. Additionally, maintaining clean coding techniques and organization further promotes readability and comprehensibility. Therefore, the top-level supervisory controller is divided into four main modules: sensors, diagnostics, controller and actuators as seen in Figure 4-1.

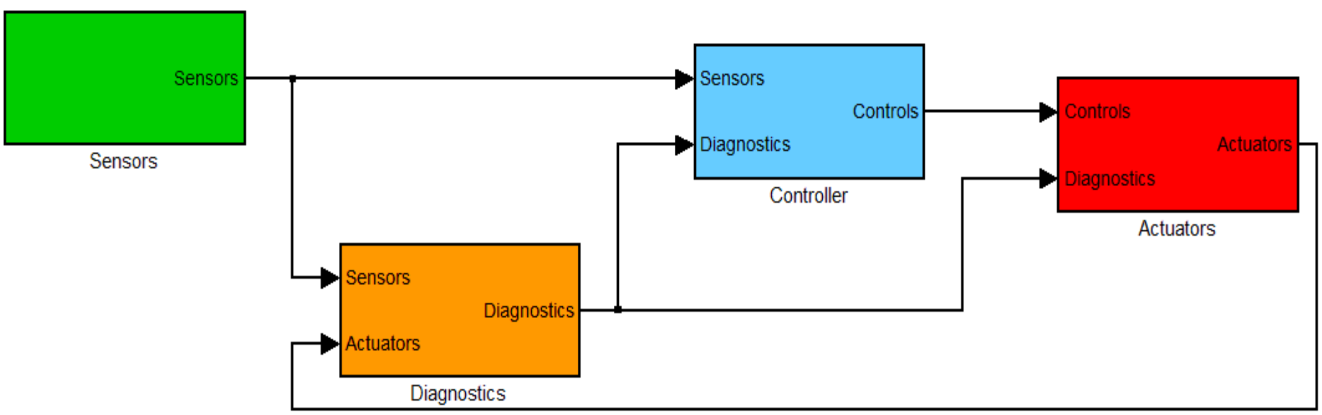


Figure 4-1. Top-Level Supervisory Controller Blocks

All data (CAN, analog, digital, etc.) read by the Sensors blocks are scaled in engineering units and converted back to their physical presentation and outputted in the Actuators blocks. The Controller block must determine the control outputs in engineering units from the sensor inputs by the necessary algorithms. The Diagnostics block converts detected failure modes into fault codes when prompted. The fault codes are the determining factor in the Safety Critical Policing Director (SCPD) [17].

4.2 Supervisory Controller Control Strategy

Currently, the bulk of the control strategies implemented is housed in the Controller block. This block consists of four subsystems: Driver Requests, Vehicle Mode Selection, Powertrain Manager and Safety Critical Policing Director as seen in Figure 4-2.

The Driver Requests subsystem is responsible for analyzing and controlling all of the driver's inputs such as the requests for starting and shutting down the vehicle. The Vehicle Mode Selection subsystem contains the E2D2 (ethanol-electric-dual-drivetrain) Manager and Regen Manager. These two managers are in charge of selecting the control strategies, Charge Depleting or Charge Sustaining modes. Powertrain Manager is made up of the FWD, RWD, and ESS managers. The RWD has a single fixed gear ratio to the axle, while the FWD engine torque has six different transmission gear ratios and a torque converter that creates multiple variable ratios of engine torque to axle torque. This results in an uneven hybrid torque split between the engine and electric motor from the driver's torque request [12]. As a result, the team decided to implement torque split between FWD and RWD in units of axle torque rather than engine/motor torque. Then the FWD and RWD managers convert the driver commanded axle torque to the appropriate engine or motor torque equivalents before sending out the torque commands to the vehicle as seen in Figure 4-3.

Among the various supervisory control strategies reviewed earlier (Section 2.2), the team decides to focus on rule-based control strategies due to the constringent timeline to have an operational vehicle in the final competition of Year 2. These strategies are fundamental control schemes that depend on mode of operation and can be easily implemented with real-time supervisory control. The rules aim to manage power flow in a HEV based on 'IF-THEN' type of control rules without taking the predefined drive cycles in consideration of its design [29]. The

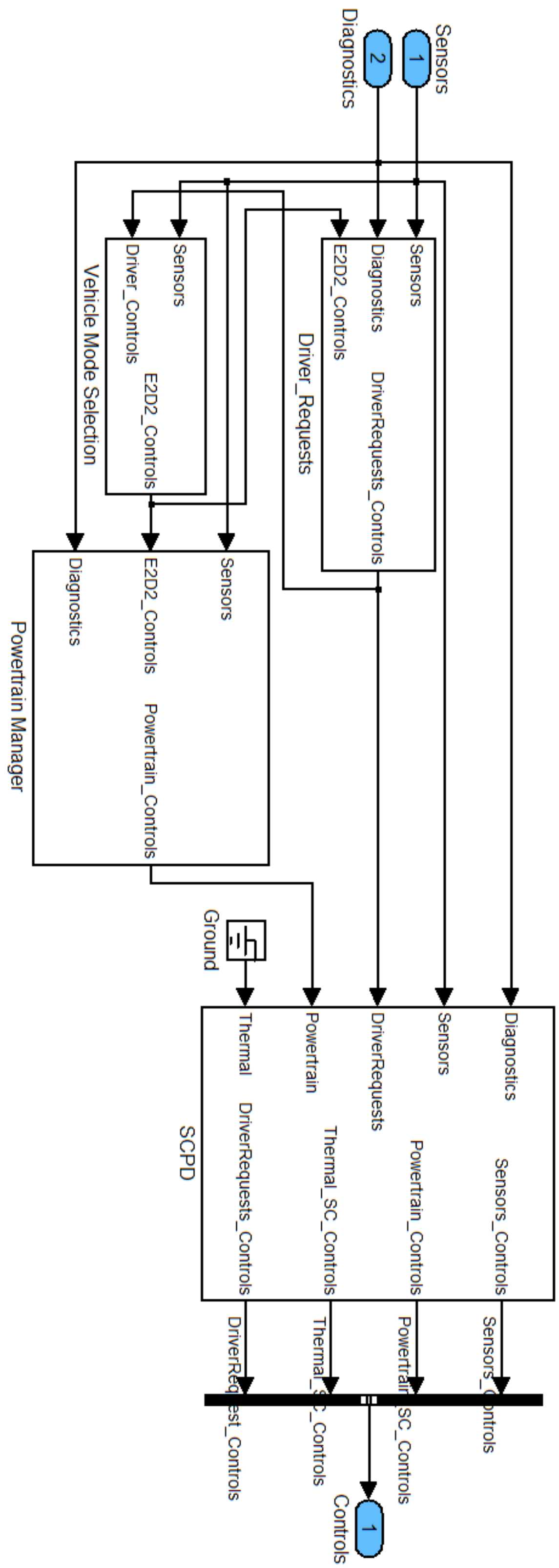


Figure 4-2. Controller Block

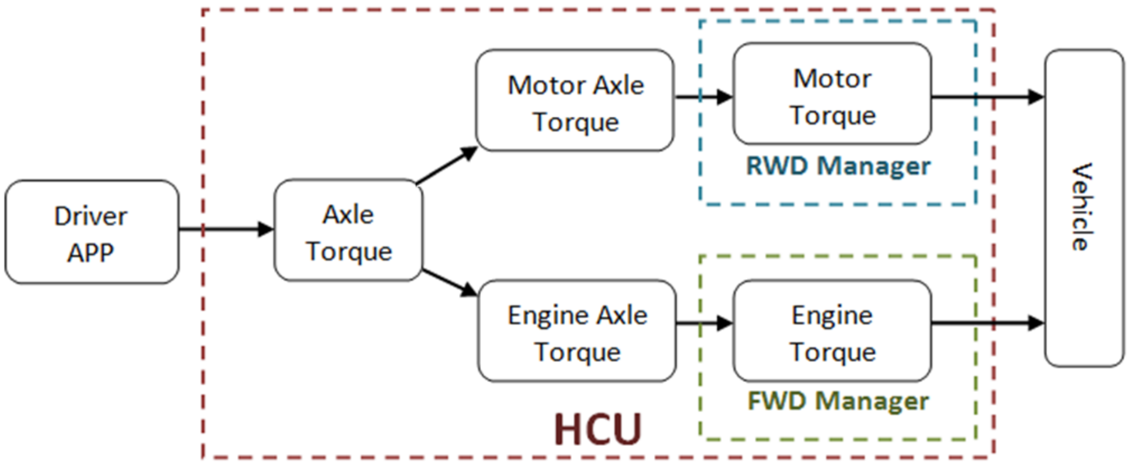


Figure 4-3. Axle Torque Split Diagram

E2D2 subsystem housed the two major control strategies that are identified to control the operations of the plug-in PTTR HEV: Charge Depletion and Charge Sustaining. It uses SOC level as the determining value of which control strategy to be selected as seen in Figure 4-4. Charge depletion occurs when the SOC level falls to the Min_SOC (yellow highlighted area) and Charge sustaining occurs when the SOC level is being charge and discharge within the range of the Min_SOC and Max_SOC (green highlighted area).

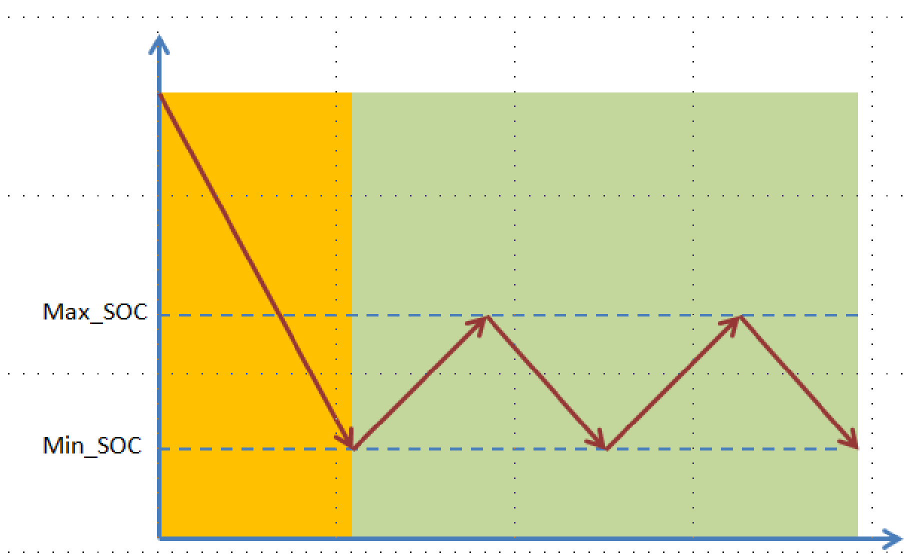


Figure 4-4. Control Strategies Based on SOC Level

4.2.1 Charge Depletion Control Strategy

The plug-in PTTR architecture operates the rear wheel drivetrain for this strategy (CDMode_RWD), and it operates as a pure electric vehicle in **"Motor Only"** mode. This eliminates tailpipe emissions and allows for a high utility factor-weighted fuel economy [30]. The positive energy flow is shown in Figure 4-5. The driver commands are read by the HCU, which will allocate all driver torque requests to the motor. Therefore the battery provides electrical energy to the motor which is then converted to mechanical energy to power the rear wheels to propel the vehicle [31]. The hybrid modes within the charge depletion strategy are shown in Table 4-1. This control strategy will be utilized until the SOC level falls below the minimum SOC limit of 20%. It is operated for both normal and aggressive vehicle operations since the electrical energy is large enough to meet all the required drive cycles. Regeneration occurs only when the APP is released in which the motor will be reversed and capture this braking energy back to the battery.

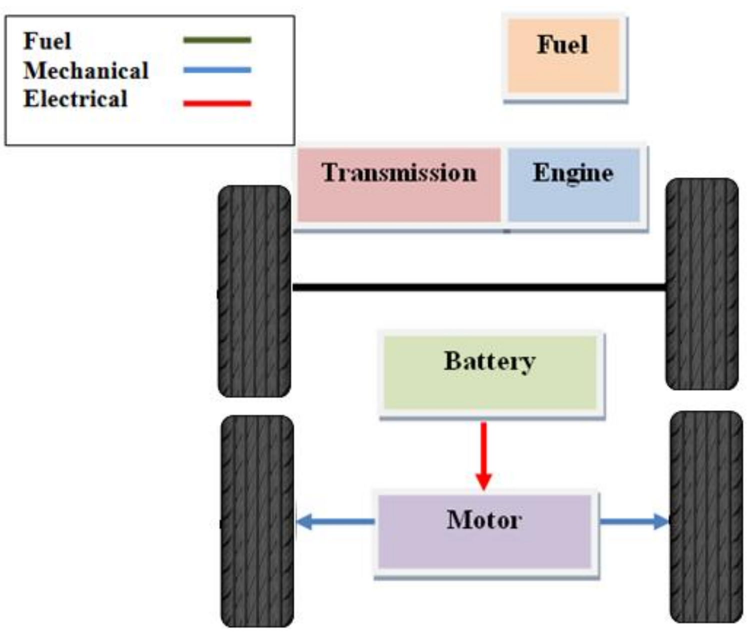


Figure 4-5. CDMode_RWD Energy Flow

Table 4-1. CDMode_RWD Mode

Control Strategy	Mode Name	Working Powertrain	SOC	Speed	APP=0 Regen	Charging Regen
CDMode_RWD	High Battery	Motor	100 - 20%	All	100Nm	N/A

4.2.2 Charge Sustaining Control Strategy

This control strategy is appropriate when the HV battery is depleted down to its charge sustaining state of charge (SOC < 20%) and the engine becomes the primary power source. Two operational modes are covered under the charge sustaining control strategy: Charge Sustaining Mode Support (CSMode_Support) and Charge Sustaining Mode FWD only (CSMode_FWD).

4.2.2.1 Charge Sustaining Mode Support

This control strategy optimizes the vehicle performance and fuel economy using a combination of "**Motor Only"** with "**Motor Assist"** (the motor to assist the engine) and incorporating "**Idle Stop"** (turning off the engine when idling) [31].

"Motor Assist" - when the engine does not supply sufficient power to achieve the driver demands, the electric motor is used to power the additional load in CSMode_Support. It is important for the motor to assist the engine to boost vehicle performance. The electric motor can be used to assist the engine to meet sudden acceleration demands since the engine is much smaller and cannot meet aggressive drives by itself. Since either or both the engine and motor can be used to propel the vehicle in CSMode_Support, there is a feedback calculation to ensure further improved vehicle performance. If the actual motor torque is insufficient in meeting the driver torque demand, the engine will be used to supply the additional power and vice versa.

"Idle Stop" - if the driver power demands are low or the vehicle is coming to a stop and there is sufficient stored electrical energy in the battery, the engine will be turned off and the motor will be the sole torque provider. This decreases the amount of time that the engine is idling and prevents the engine from performing at inefficient low loads and also limits idle fuel use. The vehicle uses RWD only to propel the vehicle up to a predetermined speed before the engine will start and provide propulsion. The vehicle performs the same strategy as charge depletion until it reaches the predetermined speed limit of 10 mph to avoid the first gear of automatic transmission. The transmission will be commanded to second gear upon engine start, avoiding the inefficient zone of the engine performing at low loads [30].

As seen in Table 4-2, the CSMode_Support does not depend on the SOC level, but does on the vehicle speed. If the commanded vehicle speed is less than 10 mph, then "**Motor Only"** occurs. If the commanded vehicle speed is greater than 10 mph, the engine becomes the main torque provider with the motor providing assisting torque as **"Motor Assist"**, allowing up to 50 Nm for charging regeneration if the driver demands are met. The charging regeneration will be disabled if the vehicle speed is above around 80 mph where only the engine power is needed to meet the driver demands. The positive and negative energy flows can be seen in Figure 4-6.

Table 4-2. CSMode_Support Modes

Control Strategy	**Mode Name**	**Working Powertrain**	**SOC**	**Speed**	**APP=0 Regen**	**Charging Regen**
CSMode_ Support	CS – Low Speed	Motor	20-21%	< 10 mph	100 Nm	N/A
	CS – Normal Speed	Engine (Motor for Regen)	20-21%	> 10 mph	100 Nm	50Nm
	CS – High Speed	Engine & Motor	20-21%	If engine alone cannot supply 80 mph	100 Nm	N/A

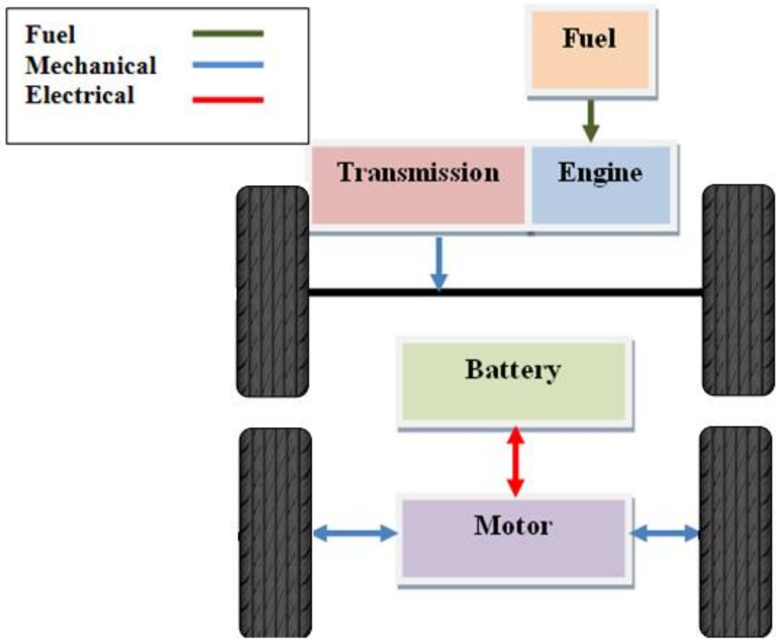


Figure 4-6. CSMode_Support Energy Flow

4.2.2.2 Charge Sustaining Mode FWD

This control strategy utilizes **"Engine Generate"** to help recharge the battery as quickly as possible to transition back to the CSMode_Support to minimize the use of the engine during idling and maximize the use of the motor for better fuel economy.

"Engine Generate" - is the primary mode that the vehicle uses in CSMode_FWD. It keeps the engine idle even at zero vehicle speed to do charging regeneration up to 100Nm of engine torque as seen in Table 4-3 [31].

Table 4-3. CSMode_FWD Mode

Control Strategy	Mode Name	Working Powertrain	SOC	Speed	APP=0 Regen	Charging Regen
CSMode_FWD	Low Battery	Engine (Motor for Regen)	< 20%	Keep engine at idle in 0 speed	100Nm	100Nm

At any time, the vehicle will be in this mode if the driver demands do not meet or exceeds the maximum torque capability of the engine for a SOC level less than 20%. This mode can be used for most normal driving conditions. The positive and negative energy flows are shown in Figure 4-7. The engine converts the fuel energy to mechanical energy and transmits the mechanical energy through gear reduction to the wheels. The mechanical energy from the extra engine load or regenerative braking will be converted to electrical energy by the motor acting as a generator and store in the battery [31].

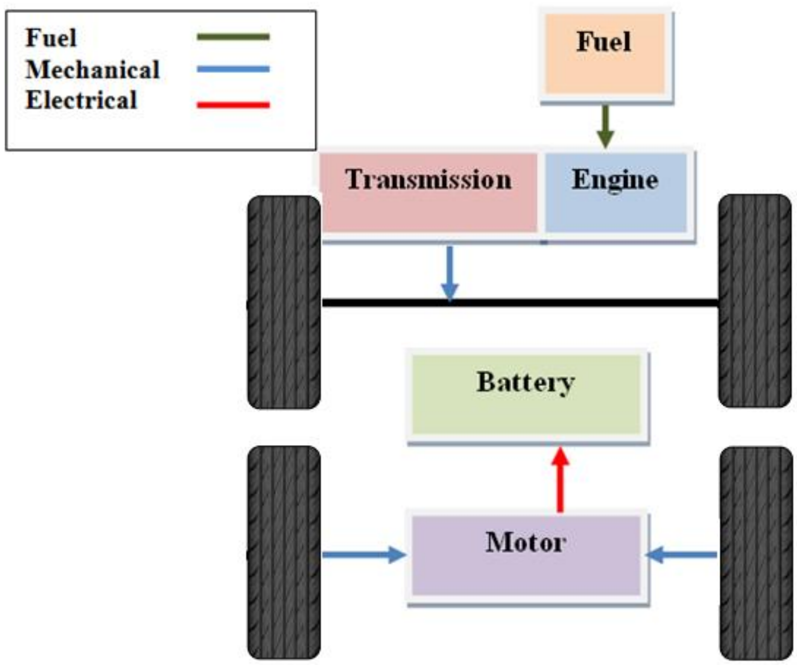


Figure 4-7. CSMode_FWD Energy Flow

4.3 Fault Detection and Mitigation Control Strategy

The overall control strategy to address and prevent safety hazards in the vehicle consists of fault detection and mitigation, by using the Diagnostics subsystem as the first line of safety protection by detecting most of the failure modes. It is responsible for "Fault Detection" by comparing the signals with their desired operating range calibrations and then setting the corresponding error bits if these signals do not fall within the limits of normal operation. The stored fault bits can be analyzed after the completion of a drive if it does not affect passenger safety or vehicle performance. The diagnostics perform actions when it detects fault bits that can be mitigated by decreasing the vehicle performance such as degraded or limp home mode if maximum tolerable limits are reached or exceeded. These limitations are done in their respective functions while safety critical functions are addressed in the SCPD (Safety Critical Policing Director). If a safety critical situation such as unintended acceleration occurs, it will be detected by the Diagnostics subsystem, but the SCPD is the final deciding factor.

The team has established 5 levels of operation and the urgency of actions to be taken at each level, as seen in Table 4-4.

- Priority level 0 is the normal operation level and indicates there are no faults diagnosed or reported by the HCU.
- A priority level 1 fault is triggered when the HCU encounters unexpected behavior of any of the components it communicates with or when it receives warning of such events from them. This fault will trigger the driver's maintenance light to indicate maintenance is required.
- A fault with a priority level 2 will cause the vehicle to enter de-rate mode. This mode will de-rate the vehicle's torque down by 30%, thus its performance. It may lead to a shutdown if the fault is not addressed immediately. The maintenance and engine lights will be turned on while the maintenance-requested indicator will be displayed on the dashboard.
- The vehicle needs to be at a full stop as soon as possible when the limp home mode is turned on. This occurs when a fault with a priority level of 3 is present. One or both the traction systems are either de-rated by 70%.
- Priority level 4 fault will cause a fast de-rate before the systems are disabled, resulting in a complete vehicle shutdown. The HV energized light, usually set steady, will be blinking

and a warning message indicating this level of fault will be displayed. This kind of fault is only triggered in cases when immediate stop of the vehicle is safer to the driver and passengers than limp home mode [13].

Table 4-4. Fault Levels and Required Action [13]

Priority Level	Status	Action Required	Immediate Action Required	Indicator
0	Regular Operation, no warnings	N/A	N/A	N/A
1	Warning, unexpected behavior	Maintenance required	No performance de-rating required	Maintenance light ON
2	De-rate Fault, not SC but will lead to shut-down if not addressed immediately	Service required	De-rate performance - 30% of motor and/or engine	Maintenance & engine lights ON, maintenance requested on display
3	Limp Home Fault, not SC but will lead to shut down if not addressed immediately	Full stop as soon as possible	De-rate performance - 70% of motor and/or engine	Maintenance & engine lights ON, maintenance requested on display
4	Safety Critical Fault will lead to shutdown	Shutdown vehicle	Shutdown of motor and/or engine immediately	Shut down indication ON

Fault Mitigation strategy is devised for Priority Levels 2-4, with the number reflecting the severity of the faults. DFMEA sessions have been conducted to define various safety compromising faults and the required detection mechanism for each. A consolidated list of system safety requirements was generated and for each of these requirements, a diagnostic algorithm based on the fault detection and mitigation strategies was designed. As more functions are identified by the DFMEA, it will be added to the test table and implemented in code also.

CHAPTER 5. SIMULATION RESULTS

5.1 Drive Cycles

A driving cycle is a series of data points in vehicle speed of versus time. It is used extensively to assess fuel consumption, emissions, and vehicle performance through simulations. Drive cycles can simulate stop-and-go as well as high speed characteristics that can closely reflect real world driving patterns. The EcoCAR2 competition has chosen four specific drive cycles representative of city and highway driving. Those together with a set of weighting factors to each of these four cycles serve to determine a meaningful combined total fuel consumption for real-world driving. Two of the drive cycles are derived from the EPA US06 cycle by splitting it into city and highway portions. The other drive cycle is the 505 which is based on the first 505 seconds of the EPA UDDS drive cycle. The last drive cycle is the HWFET. The EcoCAR2 "4-cycle" drive schedules, used for determining the VTS (Vehicle Technical Specifications) and the associated weighting factor are shown in Figure 5-1. It addresses most real-world driving conditions except for not having to directly involve A/C use and cold ambient temperatures [32].

5.2 SIL Functionality Results

As described earlier, the E2D2 subsystem houses two major control strategy branches based on the operations of hybrid vehicle: Charge Depletion (CD) and Charge Sustaining (CS). In the CS range, the minimum SOC limit is set to 20% and the maximum SOC limit to 21%. As seen in Figure 5-2, when SOC level is above 20% the vehicle mode is 1 (CDMode_RWD). When SOC level falls below 20%, the vehicle mode is 3 (CDMode_FWD) to replenish the battery to or above 20% and transitions to vehicle mode 2 (CSMode_Support) and vice versa for the vehicle to charge sustain between the SOC charge sustaining range of 20-21%.

Figure 5-1. "4-cycle" Drive Schedule [33]

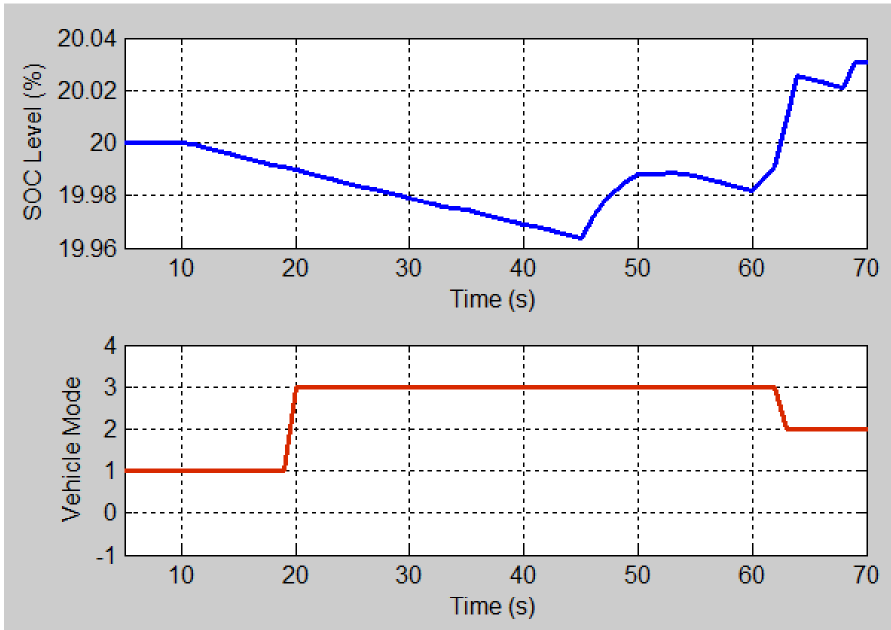
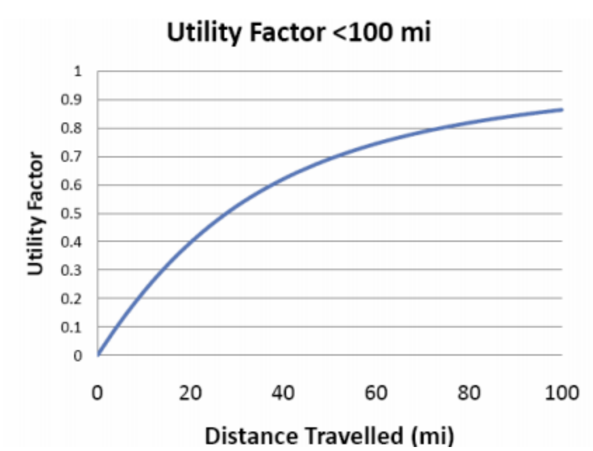


Figure 5-2. Vehicle Mode Results

In EcoCAR2 the team is scored on total vehicle energy consumption: electric energy and fuel consumptions. EcoCAR2 uses the utility factor-weighted energy consumption metric for measuring total energy consumption. As used in SAE J1711 standard, a utility factor assigns how useful the charge depleting range of a plug-in vehicle is depending on how people normally drive and how far the drive distance is. Figure 5-3 shows the utility factors depending on the distance that a plug-in vehicle can travel in its charge depletion range.



Distance (mi)	UF
10	0.22
20	0.40
30	0.53
40	0.62
50	0.69
60	0.74
70	0.79

Figure 5-3. Graph / Table for Determining the Utility Factor [33]

The CD (Charge Depletion) and CS (Charge Sustaining) fuel and electric energy consumption are to be determined by the SAE standard J1711 equations:

$$\text{Weighted Fuel Consumption}, FC_{J1711} = FC_{CD} \times UF + FC_{CS} \times (1 - UF), \tag{12}$$

$$\text{Weighted Electric Consumption}, EC_{J1711} = EC_{CD} \times UF + EC_{CS} \times (1 - UF). \tag{13}$$

The EcoCAR2 total energy consumption is:

$$\text{Total Energy Consumption} = FC_{J1711} + EC_{J1711}. \tag{14}$$

Electric energy consumption of either CD or CS mode, in watts-hour per km, (EC_{Mode}) can be calculated as Equation (15):

$$EC_{Mode} = \int_0^t \frac{P}{D} dt, \tag{15}$$

where P is the power consumed (watts) and D is the distance (km) at each time step (sec). And fuel energy consumption of CD or CS mode in liters in gasoline equivalent per 100 km, or lge/100 km, (FC_{Mode}) can be calculated as Equation (16):

$$FC_{Mode} = \int_0^t \frac{FC}{D} dt, \tag{16}$$

where FC is the fuel consumption (liters) and D is the distance (km) at each time step (sec) [33].

The SIL testing of the plug-in PTTR and HCU were performed for all four drive cycles mentioned. The results show that the team's models were able to follow the different cycles in Charge Depletion as shown in Figures 5-4a through 5-4d. The actual speeds are within ±2 m/s differences of the desired speed for all drive cycles.

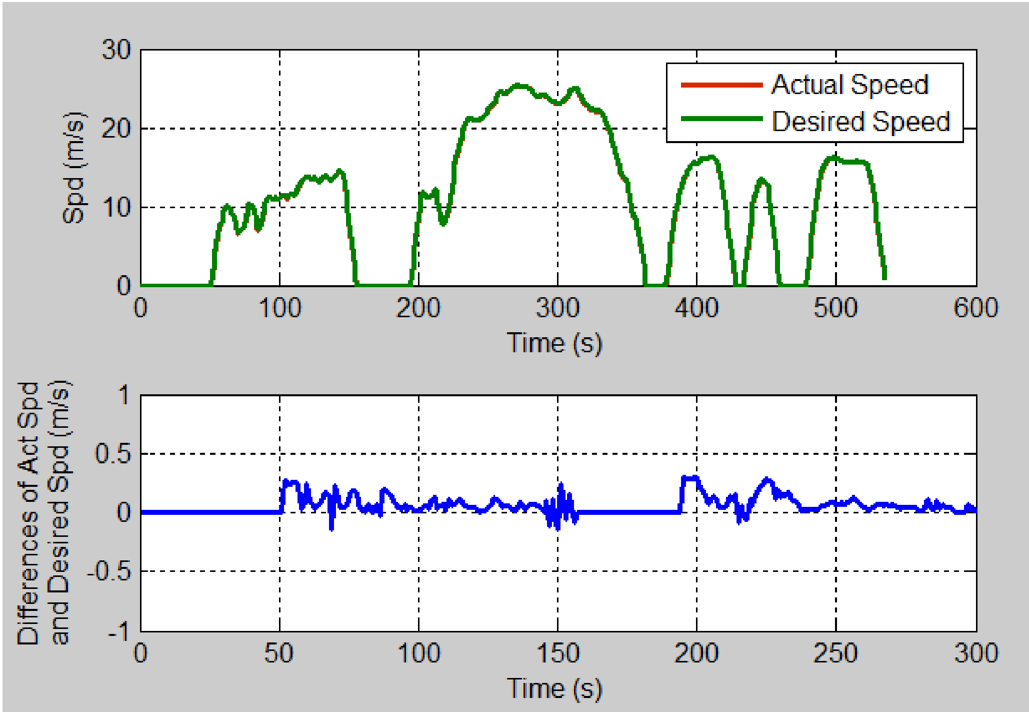


Figure 5-4a. 505 Drive Cycle Trace in Charge Depletion Mode

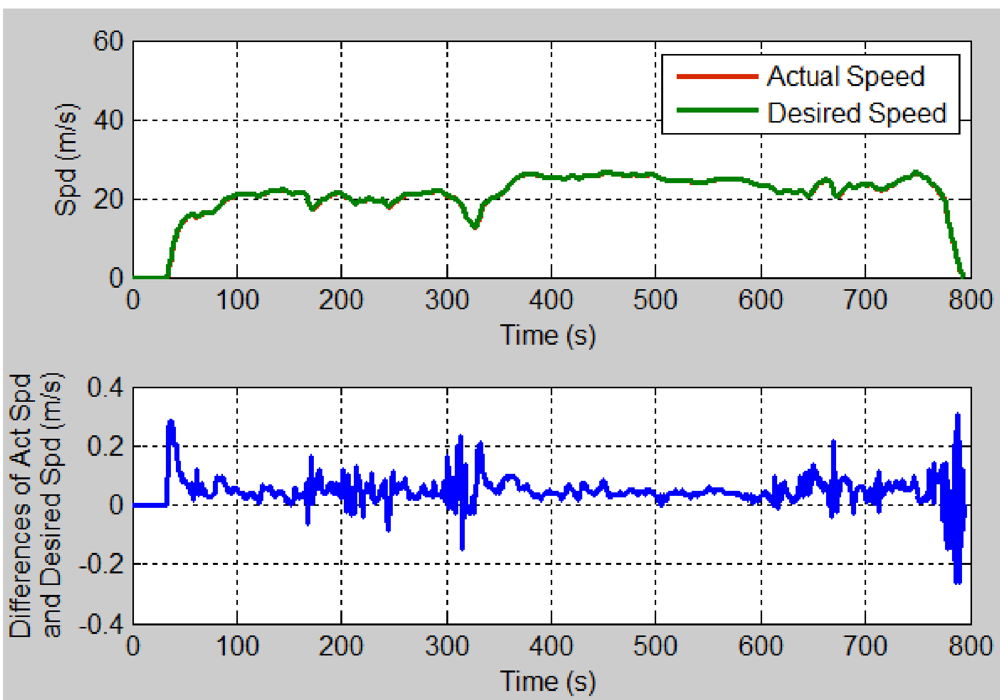


Figure 5-4b. HWYFET Drive Cycle Trace in Charge Depletion Mode

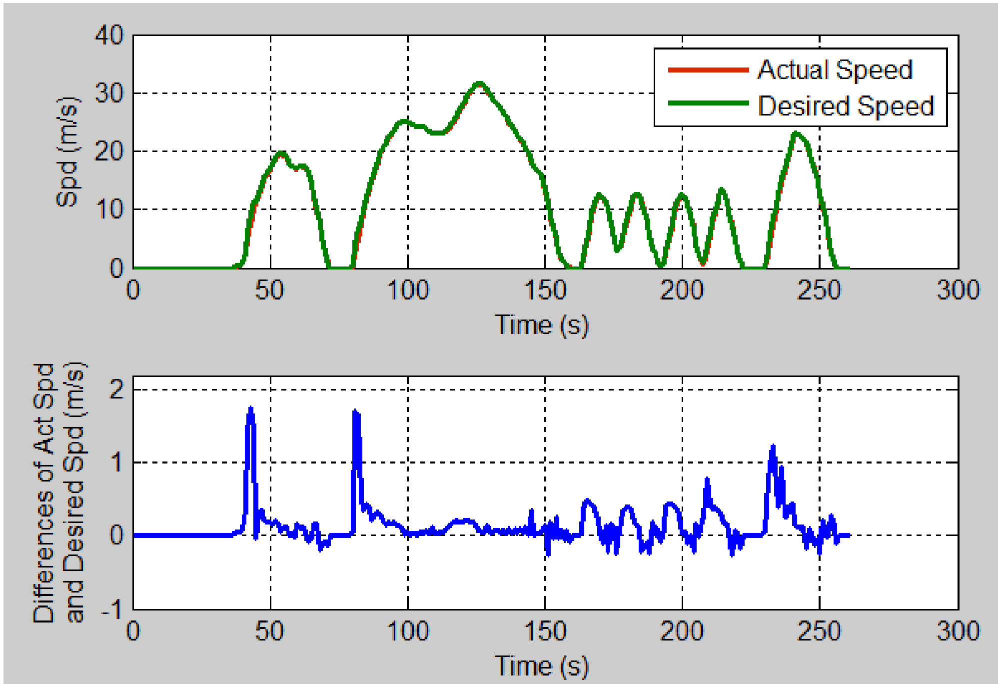


Figure 5-4c. US06 City Drive Cycle Trace in Charge Depletion Mode

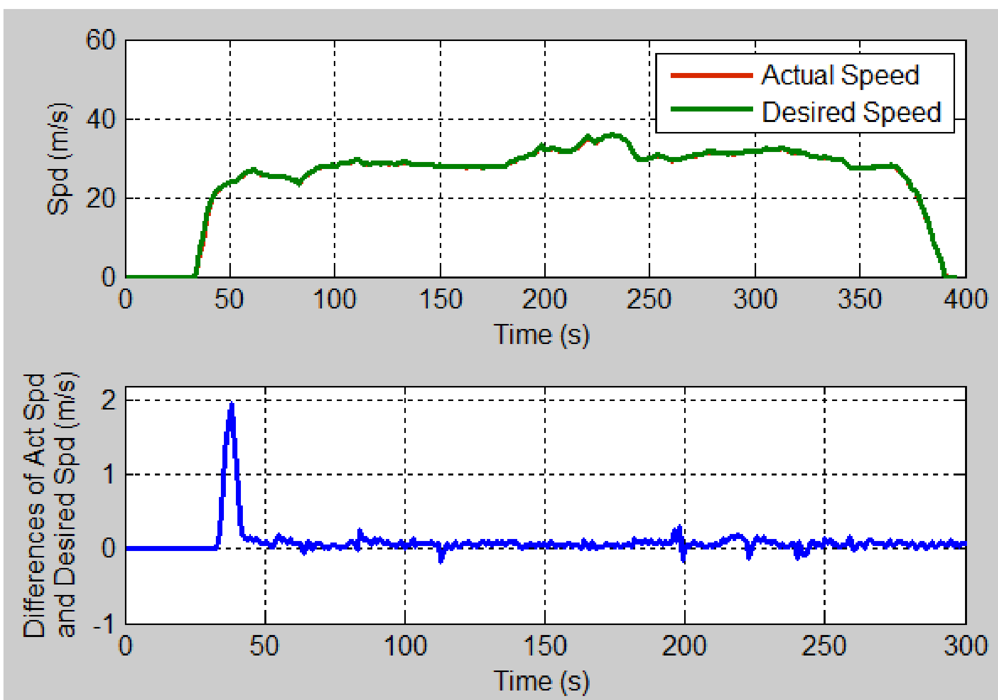


Figure 5-4d. US06 Highway Drive Cycle Trace in Charge Depletion Mode

Figure 5-5 shows the actual torque results from the engine and motor for this vehicle mode. Since the vehicle is in Charge Depletion mode, only the motor is providing torque.

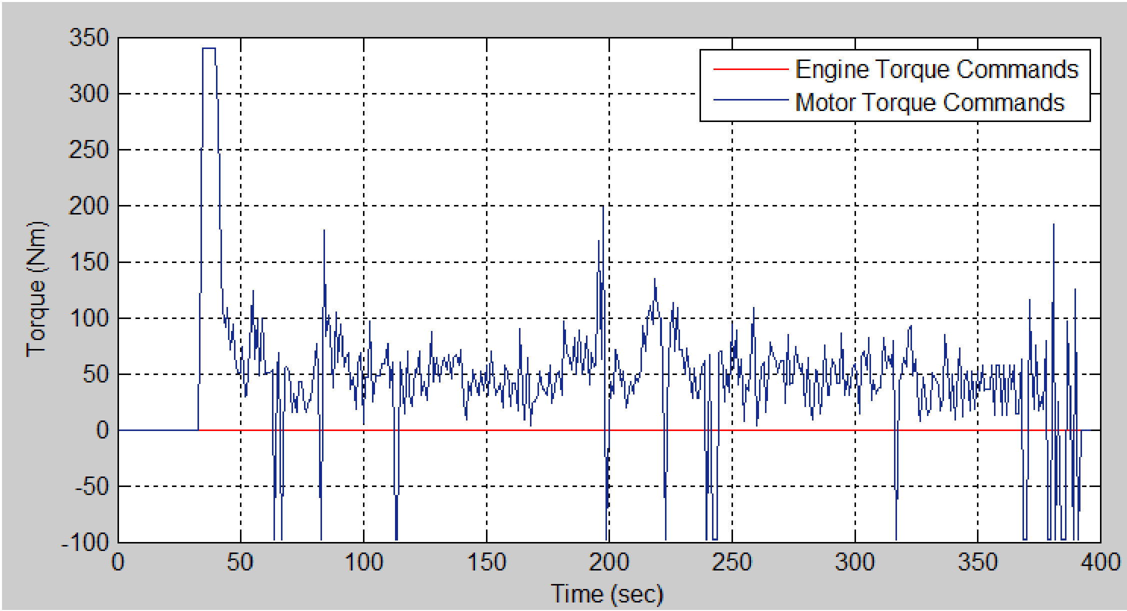


Figure 5-5. Torque Requests by HCU in Charge Depletion

In Charge Depletion mode, the electric motor is the only propulsion torque source and produces positive torque majority of the time. When the APP (Accelerator Pedal Position) is released (APP = 0) for any drive cycles, regenerative braking occurs so the motor is providing negative torque to recharge the battery as seen in Figure 5-6.

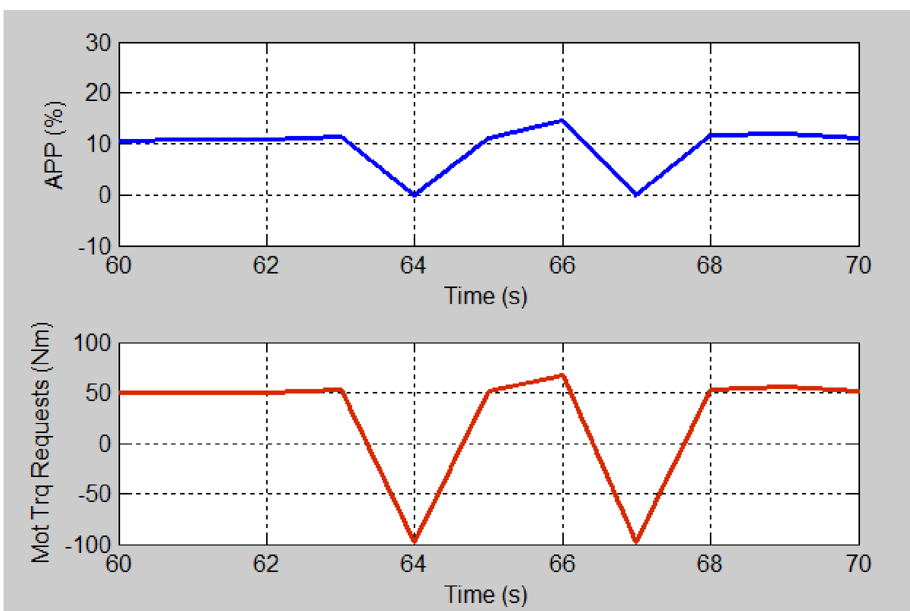


Figure 5-6. APP Release Resulting in HCU Command for Negative Motor Torque

The SIL results for the drive cycles when the vehicle is in Charge Sustaining mode are seen in Figure 5-7a through 5-7d.

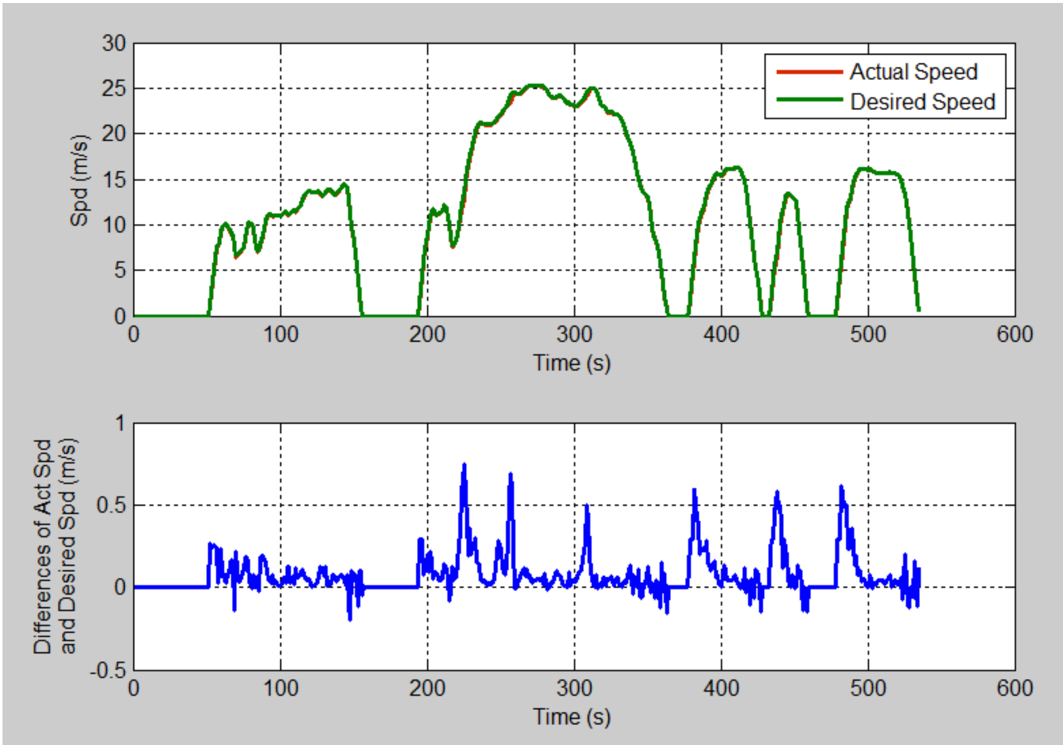


Figure 5-7a. 505 Drive Cycle Trace in Charge Sustaining Mode

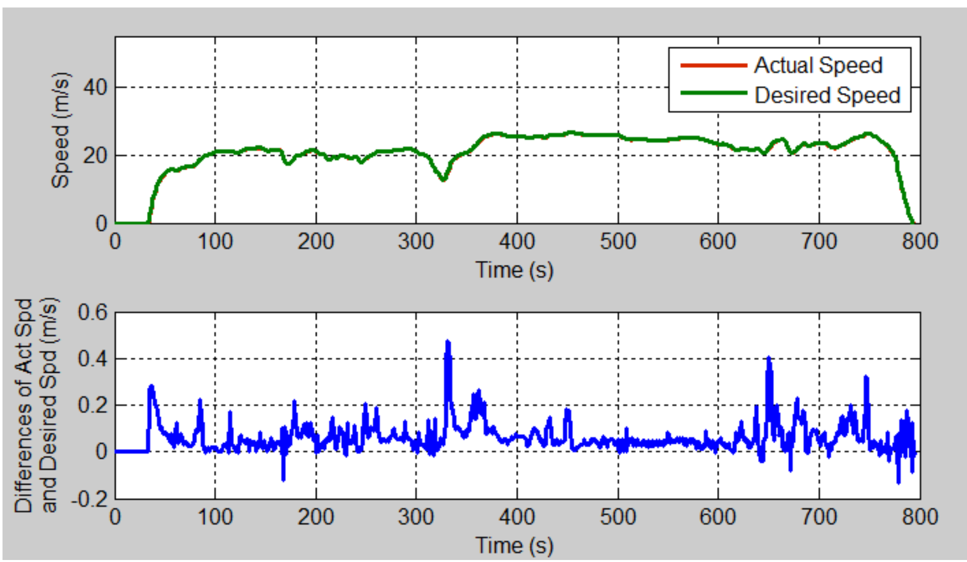


Figure 5-7b. HWFET Drive Cycle Trace in Charge Sustaining Mode

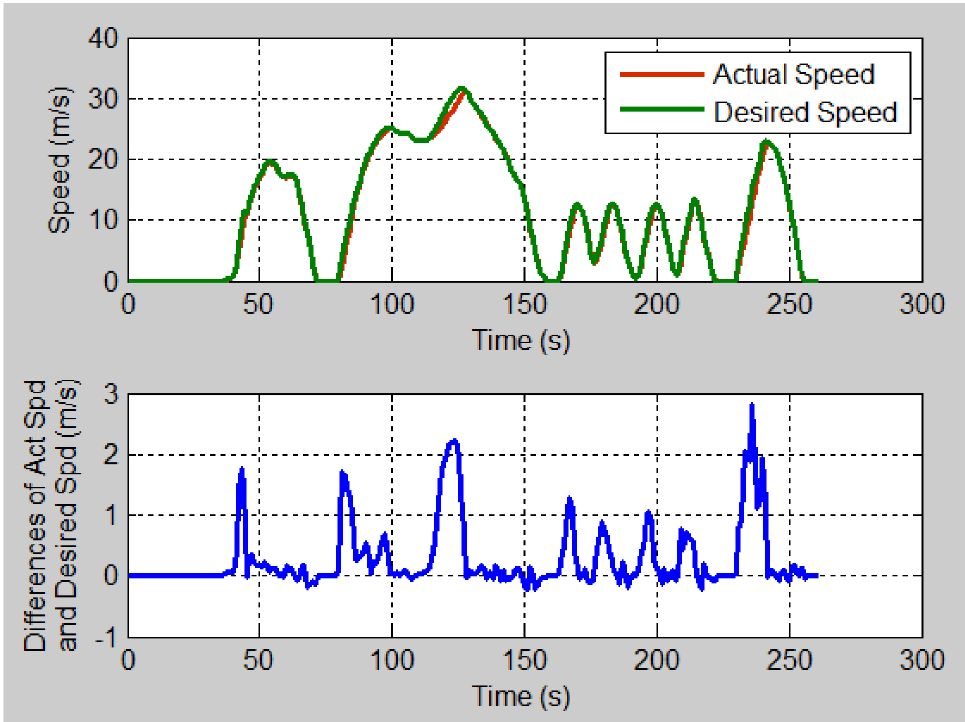


Figure 5-7c. US06 City Drive Cycle Trace in Charge Sustaining Mode

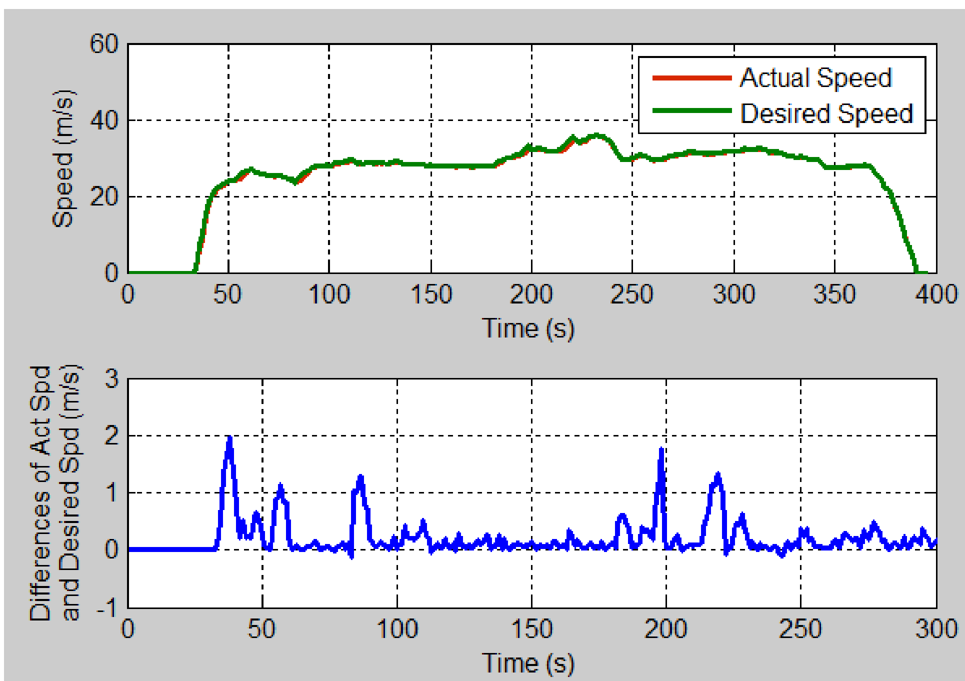


Figure 5-7d. US06 Highway Drive Cycle Trace in Charge Sustaining Mode

Figure 5-8 shows the torque results from the engine and the motor, as would be expected from both since the vehicle is in Charge Sustaining mode.

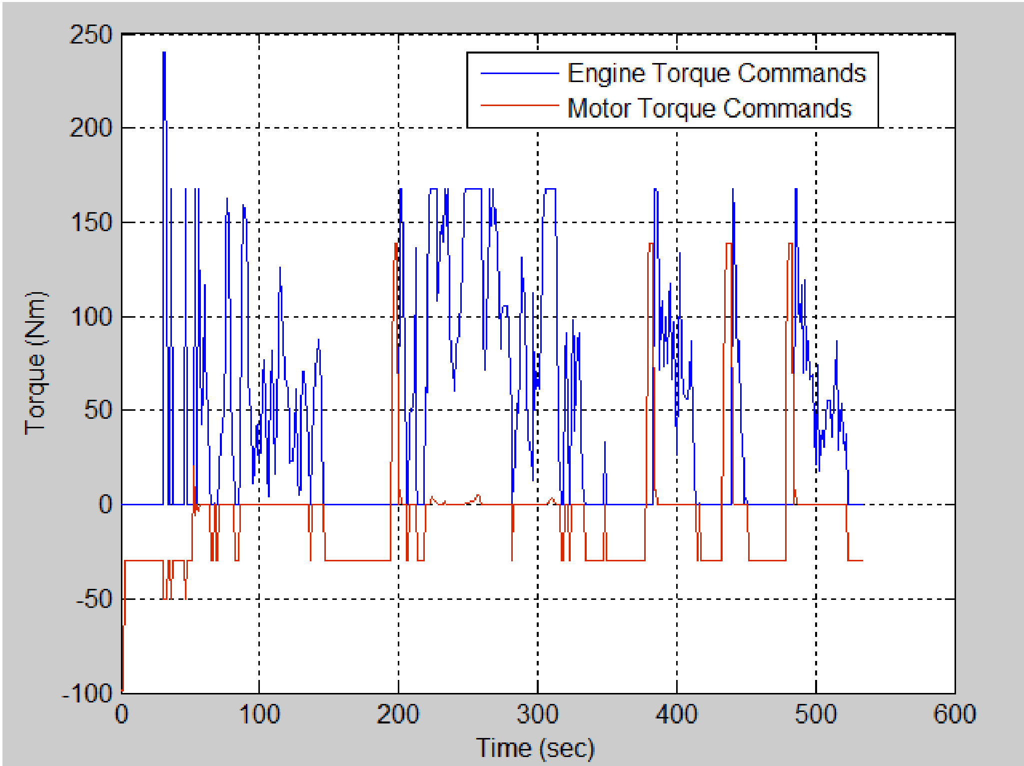


Figure 5-8. Torque Requests by HCU in Charge Sustaining

Charge sustaining mode results in higher differences between the desired and actual vehicle speeds because the engine cannot meet the harsher accelerations when the SOC is depleted too much and the motor cannot assist. The vehicle transitions between the two sub-modes of charge sustaining periodically when the battery is recharged above the minimum SOC limit of 20%. If the SOC of the battery drops below the minimum SOC limit, CSMode_FWD, the motor is used for recharging only and the motor cannot assist the engine.

However, when the battery recharges to or above the minimum SOC limit in CSMode_Support, the HCU allows the motor to assist the engine during acceleration, or turn off the engine and use the motor only to propel the vehicle at speeds below 10 mph to avoid idling. As seen in Figure 5-9 in CSMode_Support, the vehicle speeds are lower than 10 mph (4.5 m/s) up until 140 seconds during which period the engine is stopped to prevent idling, and only motor torque (positive) is used to propel the vehicle.

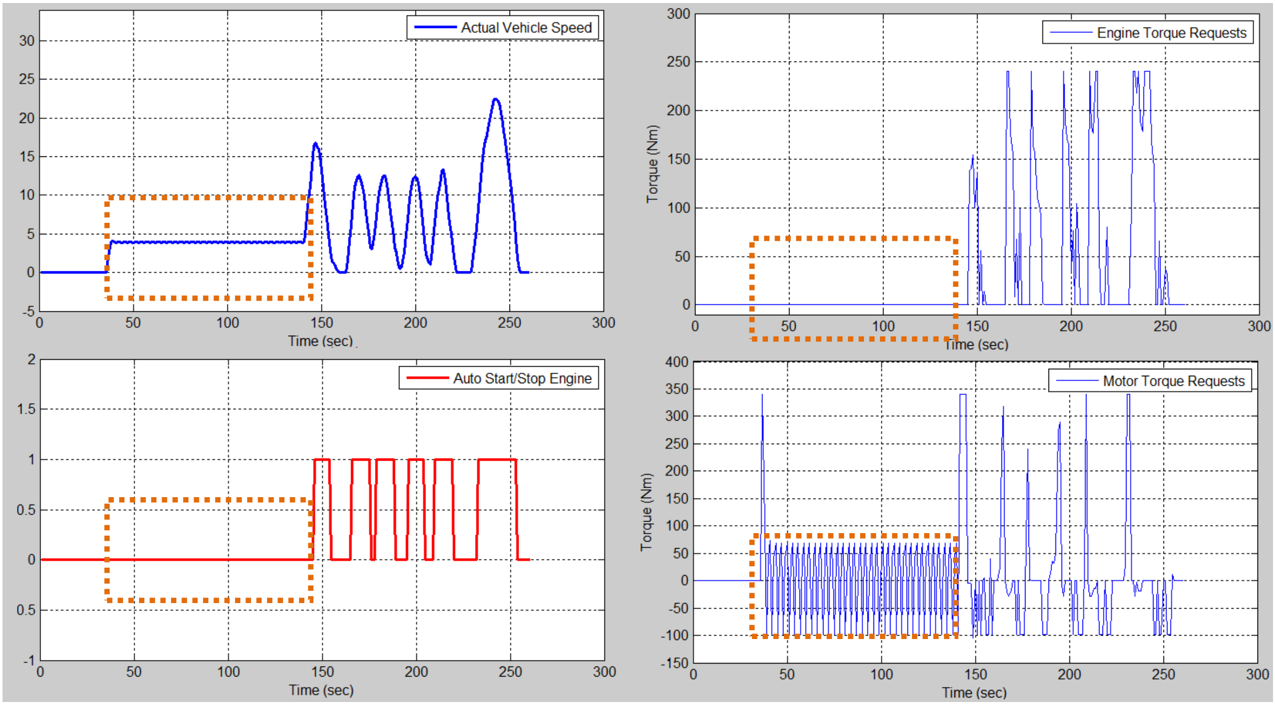


Figure 5-9. Positive Motor Torques at Low Speeds in CS Mode

Energy and fuel consumptions for each drive cycle were calculated and weighted using the listed equations and the EcoCAR2 "4-cycle" weighting to determine the energy consumption rows of the VTS are shown in Table 5-1. The team's complete VTS can be found in Appendix C.

Table 5-1. WSU VTS (Vehicle Technical Specifications)

#	Specification	Competition Design Target	Competition Requirement	WSU VTS Year 1	WSU VTS Year 2
10	Vehicle Range (<10 gallon tank)	322 km [200mi]*	322 km [200mi]*	398.4 km [249 mi] @CS	403.8 km [251 mi] @CS
11	Charge-Depleting Range (CD)	**	N/A	57.12 km* [35.7 mi]	61.18 km [38 mi] UF = 0.6
12	CD Fuel Consumption (FC)	**	N/A	0	0
13	Charge-Sustaining (CS) FC	**	N/A	9.43 (lge/100km)* [840.7 Wh/km]	10.1 (lge/100km)* [900.4 Wh/km]
14	UF-Weighted Fuel Energy Consumption (EC)	7.12 (lge/100km) [634 Wh/km]	N/A	3.96 (lge/100km)* [350.36 Wh/km]	4.04 (lge/100km)* [360.17 Wh/km]
15	UF-Weighted AC Energy Consumption EC	**	N/A	157.5 (Wh/km)*	162.8 (Wh/km)*
16	UF-Weighted Total EC	634 (Wh/km)	N/A	507.9 (Wh/km)*	523 (Wh/km)*

(*) Evaluated by using the EcoCAR2 combined "4-cycle" weighting method - EC2 E&EC Cycle

5.3 SIL Diagnostics and SCPD Results

Since the majority of Year 2 focuses on developing the functional code for the supervisory controller, the team implemented the safety algorithms to detect and prevent faults that are recorded as the areas of greatest concerns (highest RPNs) only according to the team's DFMEA. Table 5-2 summarizes the safety functions that were implemented to the supervisory controller according to the 5 levels of operation and the urgency of actions as seen earlier in Table 4-4. The DFMEA entries used to identify these failure modes can be seen in Appendix D.

Table 5-2. Safety Algorithms Implemented in HCU

Safety Algorithm	Description	DFMEA Location
Wheel Slip Prevention	Diagnostics detects when the wheels start to slip, so the HCU reduces torque to the wheels to avoid an ABS event. If the wheels continue to slip, the SCPD will disable one of the drivetrain (FWD or RWD) depending on SOC - Priority level 2 may escalate to level 4.	SC.3
Unintended Acceleration Mitigation	Diagnostics detects that an unintended acceleration occurs and depending on which drivetrain was responsible for it, disables the drivetrain (FWD or RWD). Priority level 4.	SC.1
Loss of CAN Communication Mitigation	Effective CAN communication is necessary for the HCU's functionality. If any CAN error occurs, the vehicle needs to be shut down as soon as possible to avoid endangering the passengers. Priority level 4.	SC.5
Engine Torque Mitigation	Diagnostics and SCPD detect the mismatch error between the HCU's engine torque requests and the actual engine torque and decide when to degrade (level 2) or limp home (level 3) or shutdown (level 4) the FWD.	E2D2.6
Motor Torque Mitigation	Diagnostics and SCPD detect the mismatch error between the HCU's motor torque requests and the actual motor torque and decide when to degrade (level 2) or limp home (level 3) or shutdown (level 4) the RWD.	E2D2.6

5.3.1 Wheel Slip Prevention

The supervisory controller will need to detect the wheel slipping early and reduce wheel torque to avoid engaging the ABS for the sake of allowing for safe regeneration and preventing slip conditions that are bad for the tires and vehicle stability. Mathematically, a wheel slip is defined as following equation:

$$S_w = w - \frac{v}{2\pi r} \neq 0\,, \tag{17}$$

where w is rotation of the wheel, v is vehicle speed and r is wheel radius. CAN signal WhlSlpSt will indicate a positive wheel slip the moment it occurs due to excessive wheel spinning ($S_w \neq 0$). The HCU will read this signal and reduce the torque request to prevent the WhlSlpSt signal from evolving to a wheel slip fault and subsequently engaging the ABS unintended [34].

When the value of WhlSlpSt indicates that the wheels are starting to slip (WhlSlpSt = 2), the propulsion torque (engine or/and motor) will be multiply by a wheel slip factor which decreases until the WhlSlpSt indicates that the wheels are no longer slipping (WhlSlpSt = 0). Figure 5-10 shows how the torque multiplying factor keeps decreasing while the slip is still detected.

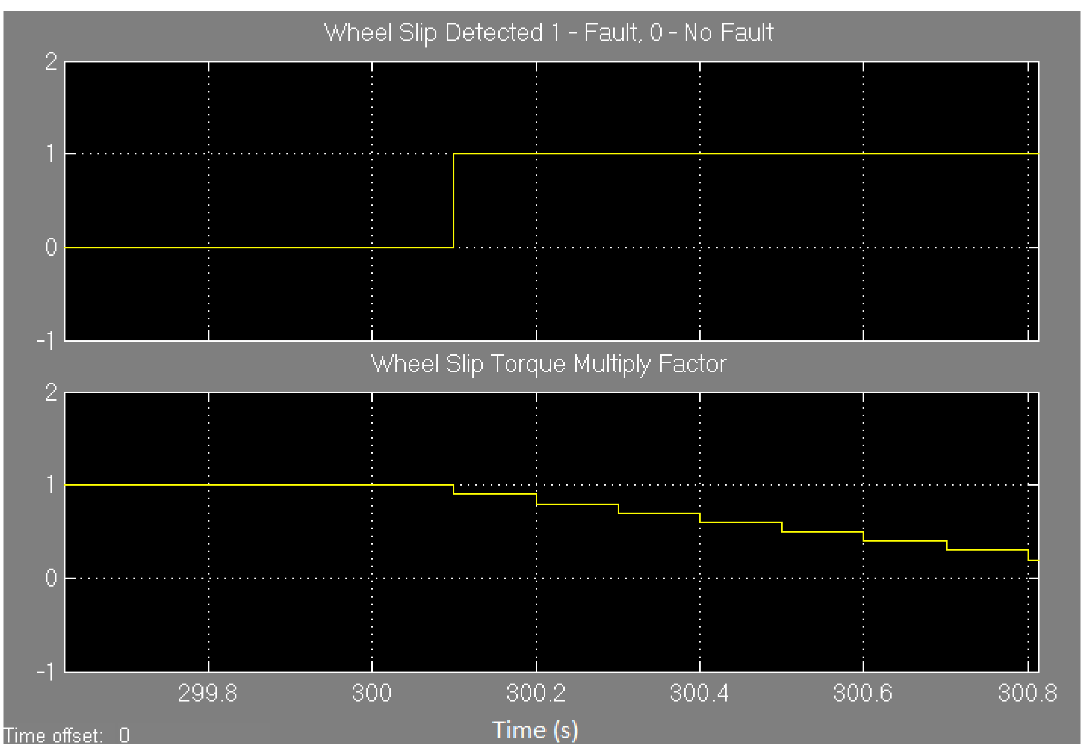


Figure 5-10. Wheel Slip Detection and Mitigation

5.3.2 Unintended Acceleration (UA) Mitigation

Unintended acceleration is a safety critical fault because it endangers the passengers and other vehicles and should be avoided at all times. An unintended acceleration occurs when the vehicle speed increases although the driver is not pressing the accelerator pedal or is pressing the brake pedal. It can occur due to many factors such as corrupted CAN or analog signals or incorrect motor and engine torque coordination. Regardless, a safety algorithm needs to be designed that can react and mitigate all the situations that can result in an unintended acceleration. In this example, an unintended acceleration was detected by the HCU at the 300-second mark as seen in Figure 5-11, which will trigger to HCU to slow the vehicle down to a stop. As seen Figure 5-12, the driver pressed on the brake pedal to slow down the vehicle but the vehicle speed keeps on increasing, causing the actual vehicle speed to be different from the desired vehicle speed after the unintended acceleration fault was detected. However, the HCU has disregarded the driver’s commands, because an unintended acceleration is a safety critical fault, and proceeded to slow the vehicle down to a stop.

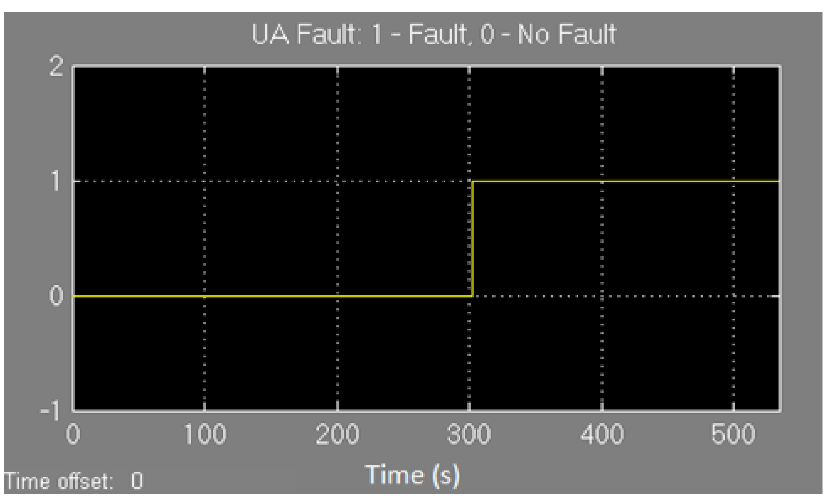


Figure 5-11. UA (Unintended Acceleration) Fault Detected

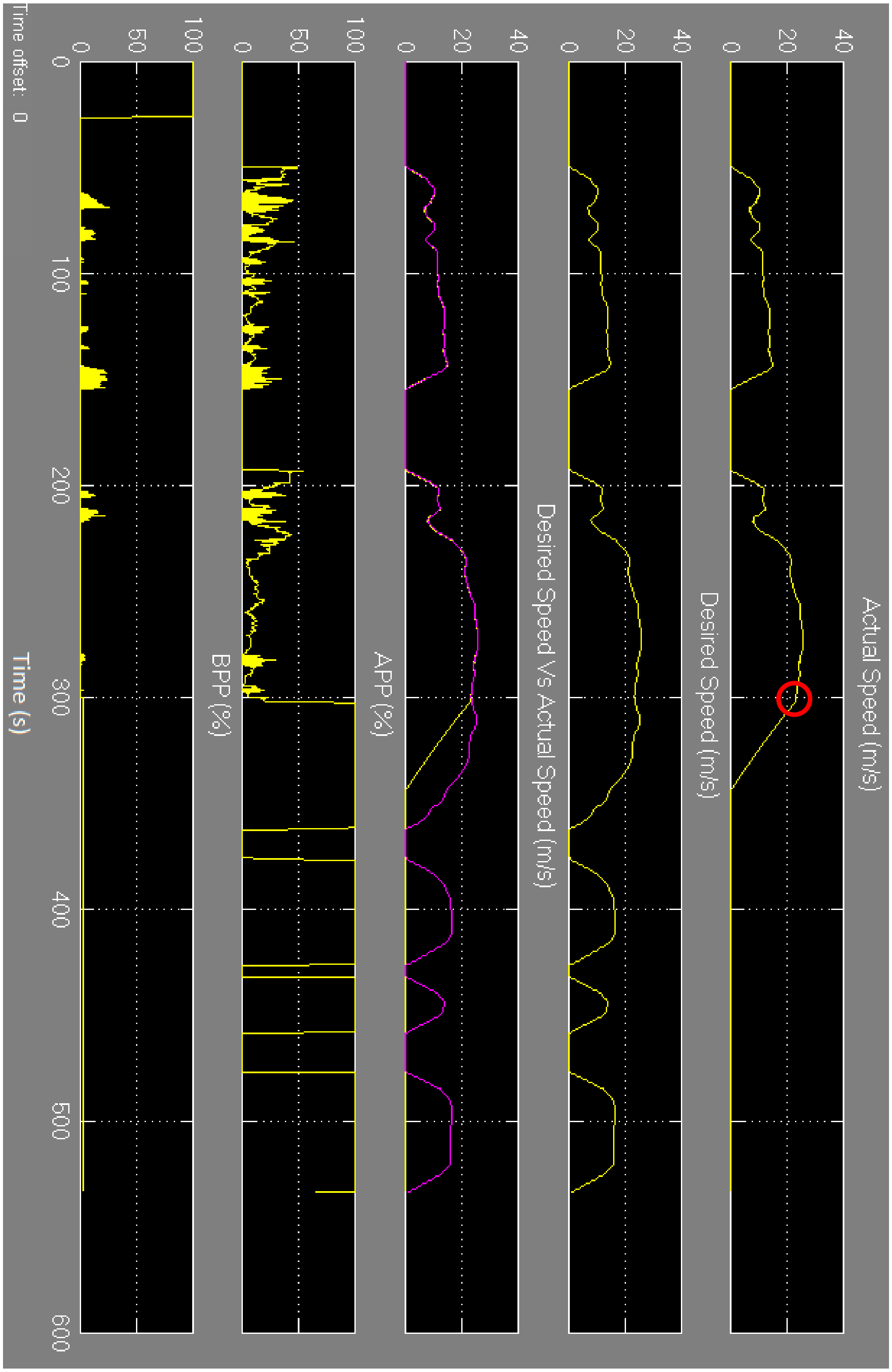


Figure 5-12. UA Fault Mitigation by HCU

5.3.3 Loss of CAN Communication Mitigation

Since the supervisory controller relies on many CAN messages as parameters to give commands, the loss of CAN communication will damage the vehicle's functionality and endanger the passengers. The supervisory controller was designed to react to this situation by disabling the vehicle propulsion the moment the loss of CAN communication error is detected even if the error occurred for 1 second or less and was resolved immediately. As seen in Figure 5-13, the CAN signal fault was detected at 300 seconds. The HCU outputs zero torque commands for the engine and/or the motor and results in the vehicle slowing down. At shortly after 380 seconds, shown in Figure 5-14, the driver pressed the brake pedal so the vehicle comes to a stop faster. If the driver did not press the brake pedal, the vehicle would eventually slow down to a stop.

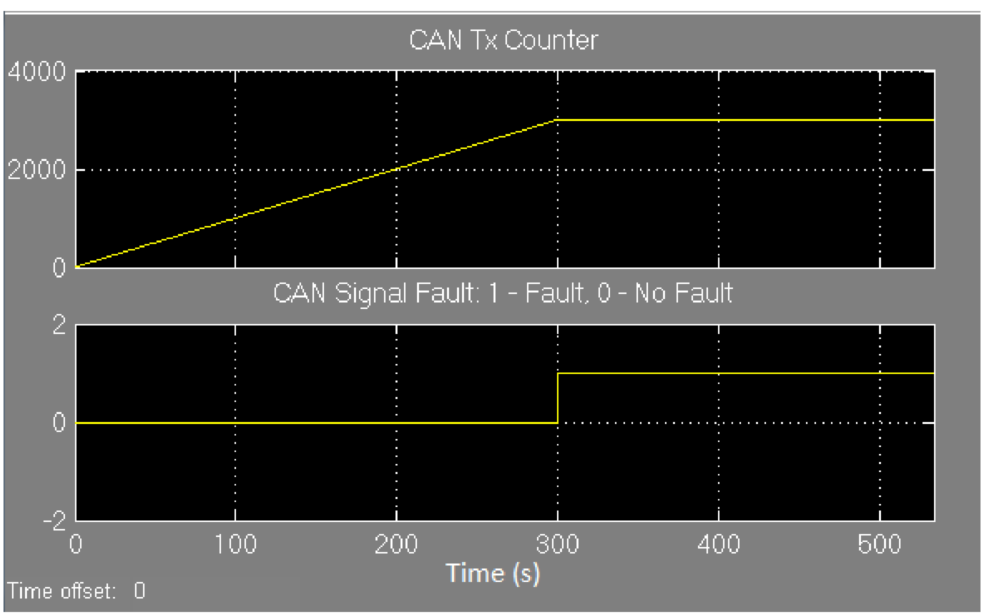


Figure 5-13. CAN Signal Fault Detected

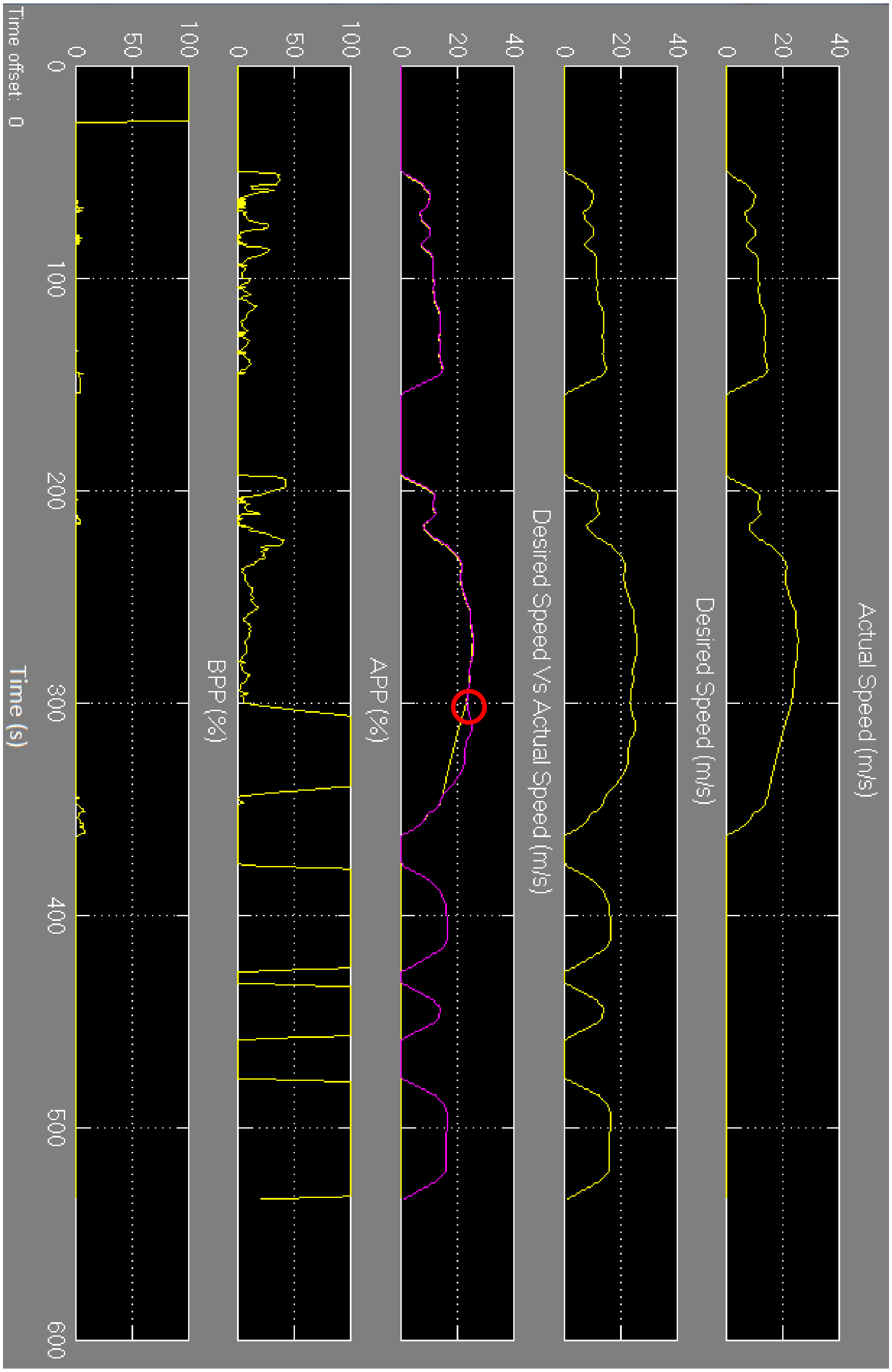


Figure 5-14. CAN Signal Fault Mitigation

5.3.4 Engine Torque Coordination

A failure related algorithm detecting and mitigating the mismatch engine torque between engine torque command and actual engine torque provided by the engine is required to address when the engine becomes malfunctioned by providing too much or not enough torque. The extent of the mismatch will result in the engine to be degraded, limp home or be shut down. The SIL results can be seen in Figures 5-15 through 5-17. Mismatch engine torques higher than the "Degraded Calibration Point" will result in the engine torque requests to be reduced by 30%. Whereas mismatch engine torques higher than the "Limp Home Calibration Point" will result in the engine torque requests to be reduced by 70%. Ultimately, mismatch engine torques higher than the "Safety Critical Calibration Point" will result in the HCU disabling the FWD functionality (eng APP recast request, as explained earlier in Section 3.3.1, is reduced to zero).

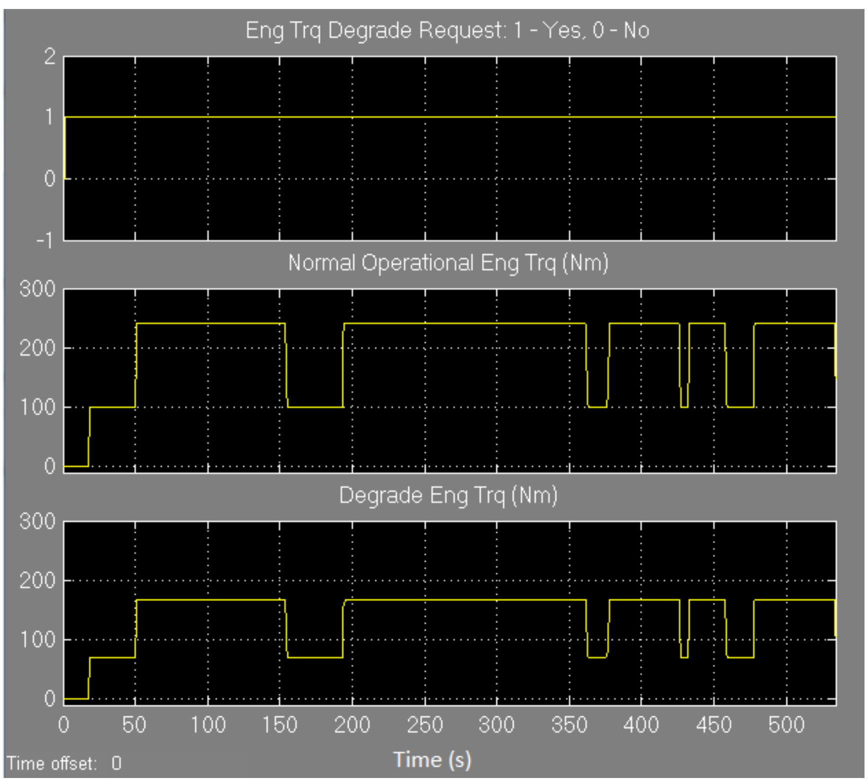


Figure 5-15. Degraded Engine Torque

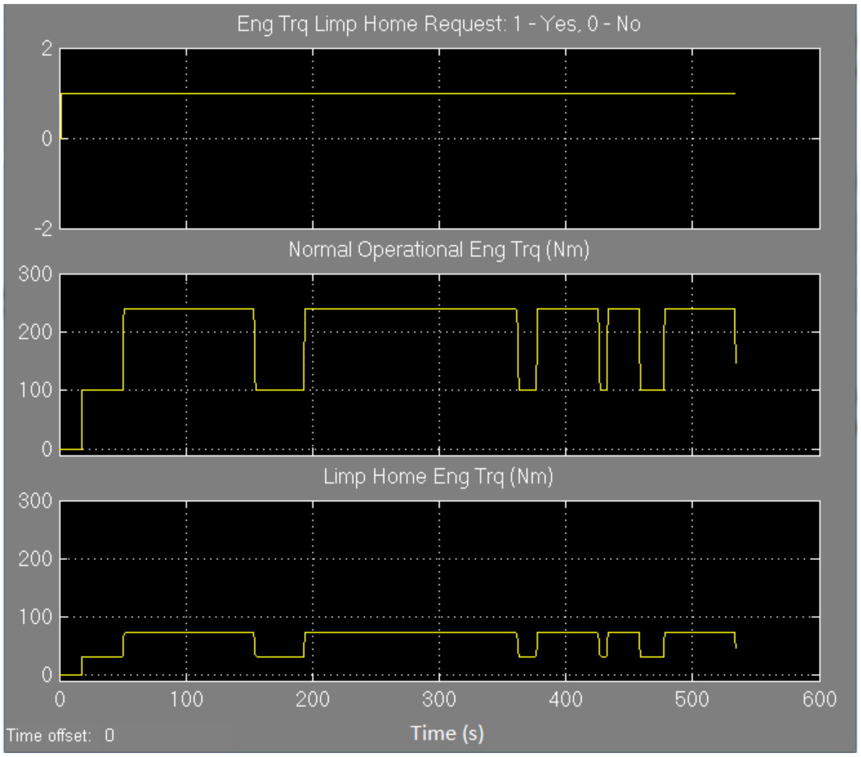


Figure 5-16. Limp Home Engine Torque

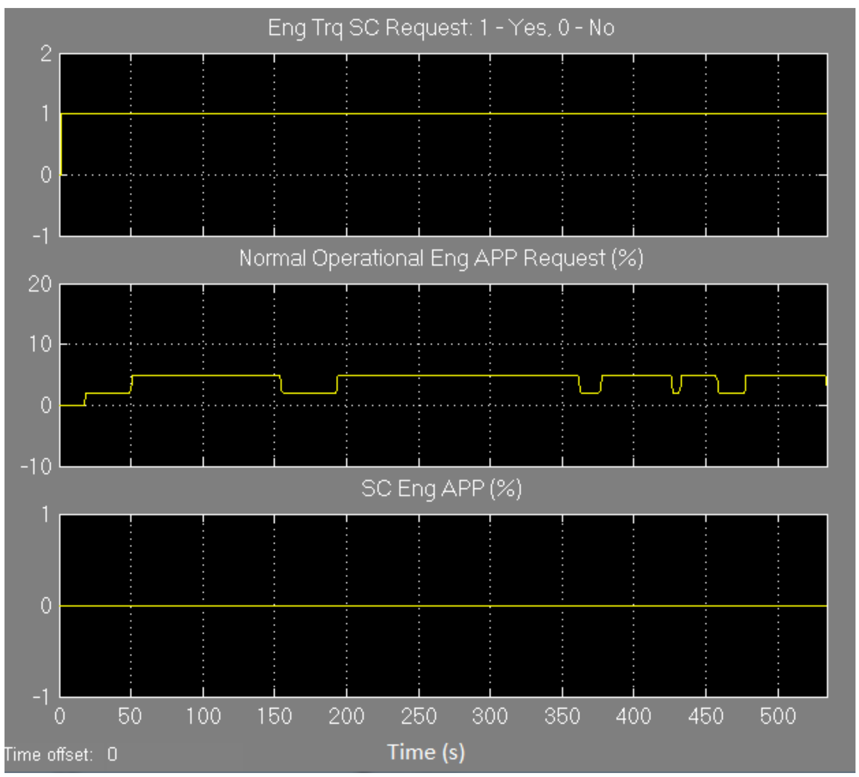


Figure 5-17. Engine Torque Requests Stopped with FWD Functionality Shutdown

5.3.5 Motor Torque Coordination

The failure related algorithm detecting and mitigating the mismatch motor torque between motor torque command and actual motor torque is exactly the same as the engine algorithm described in Section 5.3.4. The HCU will reduce the motor torque requests accordingly to the extent to which the mismatch values exceed. If it is above the degraded, limp home, or safety critical calibration points then the motor torque requests will be reduced accordingly or the motor will be shut down as seen in Figures 5-18 through 5-20.

The SIL results show that the HCU handled the faults that were discussed in this section successfully. It is able to detect these faults quickly and perform the necessary actions to reduce the severity of the symptoms. These safety algorithms are the minimum requirements that are to be implemented in the actual vehicle in Year 2 to ensure safe vehicle operation, covering the most significant faults that can affect the passengers' safety. There are more fault cases and safety algorithms that are already identified; some examples can be seen in Table 5.3. They can be implemented in the Year 3 since these additional faults are more influential on vehicle performance, but less on the probability of it occurring and compromising passengers' safety.

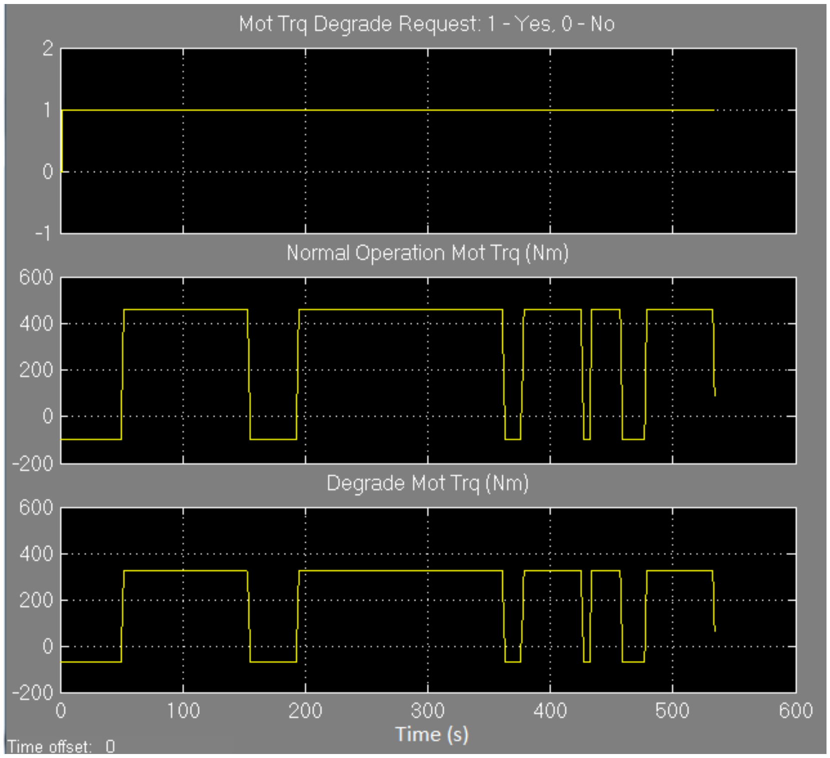


Figure 5-18. Degraded Motor Torque

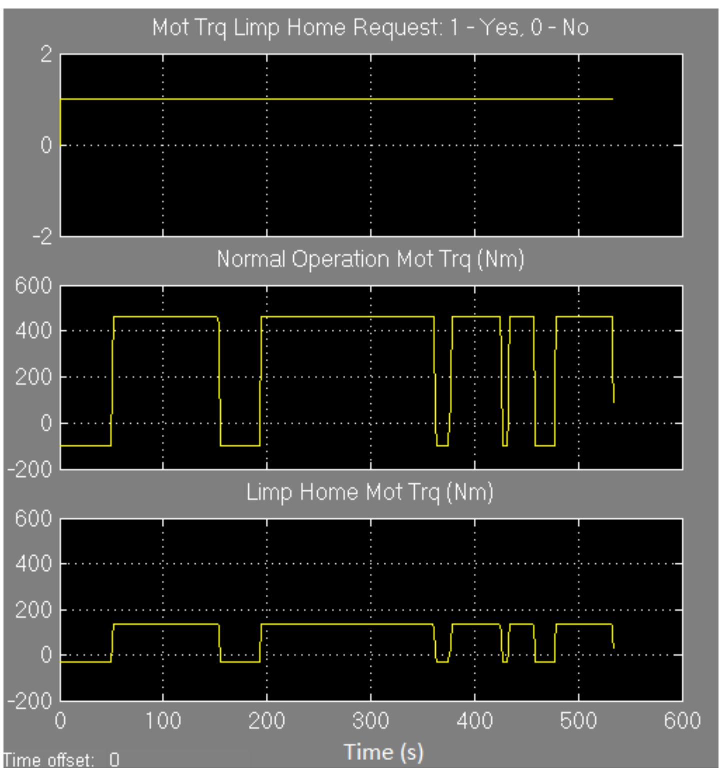


Figure 5-19. Limp Home Motor Torque

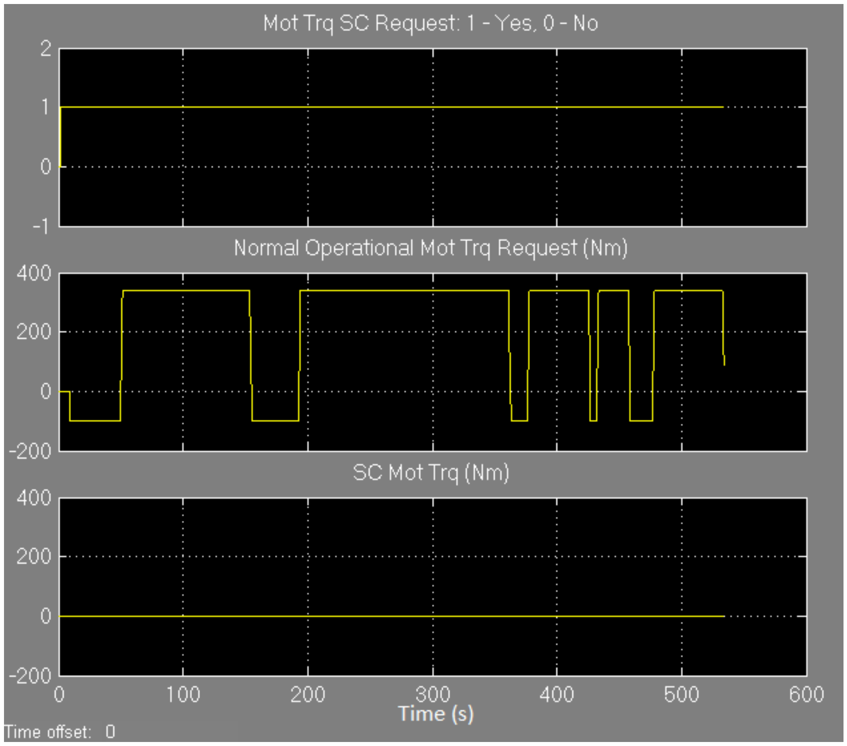


Figure 5-20. Motor Torque Requests Stopped with RWD Functionality Shutdown

Table 5-3. Fault Cases and Safety Algorithms to be Implemented in Year-3

Item Failure Modes	Subsystem	Functions	DFMEA Location
Failure to meet desired speed during Regeneration though the road	Diagnostics	During Regen, if eng is not meeting the driver request for "TBD" time, decrease Regen slowly until zero. If zero Regen & eng is still not meeting driver power request, stored fault code for later analysis.	E2D2: 7
	SCPD	N/A	
APP released/slowed too quickly by Regen braking	Diagnostics	If APP released & vehicle speed decreases too much > "TBD" value at one time, flag error for farther future calibration.	E2D2: 15
	SCPD	N/A	
Mot stops delivering required power before/after eng starts delivering power	Diagnostics	MCU Motor Trq - HCU Motor Trq Req > negative MotTrq_Mismatch (TBD) will result in a fault to be generated. Engine assists if possible.	E2D2: 10, 11
	SCPD	N/A	
Eng stops delivering required power before/after mot starts delivering power	Diagnostics	ECM Engine Trq - HCU Engine Trq Req > negative EngTrq_Mismatch (TBD) will result in a fault to be generated. Motor assists if possible.	E2D2: 12, 13
	SCPD	N/A	

CHAPTER 6. CONCLUSION

This thesis has demonstrated and provided results for the effective use of SIL to develop and validate a PTTR plug-in hybrid architecture and its control system. First the requirements between the supervisory control system and each controller in the system were identified. Then DFMEAs were considered to create or update the requirements. Both sets of requirements were used in the development of supervisory controller and vehicle plant model. The component plant models were designed to react and respond similarly as their hardware counterparts and used to simulate vehicle fault behaviors to validate the supervisory controller. Also, the development of the supervisory controller takes into consideration that it will be run on a HIL setting eventually. Consequently, all codes were done using Mathworks Simulink, kept simple, and provided with enough coding flexibility for an easier transition to HIL. All the signals created and routed follow the same naming convention as the DBC files provided by EcoCAR2 and GM so CAN communication can be performed easily when the team transitions from SIL to HIL testing. The SIL results demonstrated the supervisory controller's ability to operate the FWD and RWD drivetrains separately as well as in a blend mode for updating the team's VTS. Calculations associated with the VTS results clearly show that the vehicle can achieve better fuel economy by utilizing the supervisory controller developed in this thesis. Additional SIL results are shown to address certain safety issues that may arise during vehicle operation as identified by the team's DFMEAs. All faults simulated in the vehicle plant model were mitigated by the supervisory controller successfully as expected. With all these it is considered that the supervisory controller has been SIL-tested successfully for all the requirements mentioned and is ready to be uploaded to the actual HCU for HIL validation.

Many meaningful works can be extended from this thesis in the future, more as the next phases along the line of vehicle control strategy development and testing. First, HIL is to be performed to validate the supervisory controller before VIL testing. The controller portion of the SIL model will be uploaded to become the supervisory controller model for MABXII as shown in Figure 6-1. The plant models portion will be uploaded as the vehicle plant model for the HIL simulator as shown in Figure 6-2. Since the supervisory control algorithms inside the Controller subsystem are using the same naming conventions as identified by the DBCs and ICDs, the control algorithms will need no change in the HIL. The main changes between SIL and HIL are the sensors and actuators blocks. Signals in these blocks will be physical signals (e.g. CAN, analog and digital) in the HIL supervisory controller and plant models while they are only simulated in the SIL model as seen in Figure 6-1 and 6-2. Second, real-world data from VIL testing can be used to further optimize the variables and improve algorithms that were implemented. The current strategy is only optimized for fuel economy but a performance mode could be added that further opens the engine operating range. And lastly, the thermal components in existing plant models and the associated thermal controllers were not designed in this thesis. Future model developments should incorporate such controller and the temperature effects to more accurately simulate fuel economy and performance, and to better address thermal-related phenomena such as cold-start.

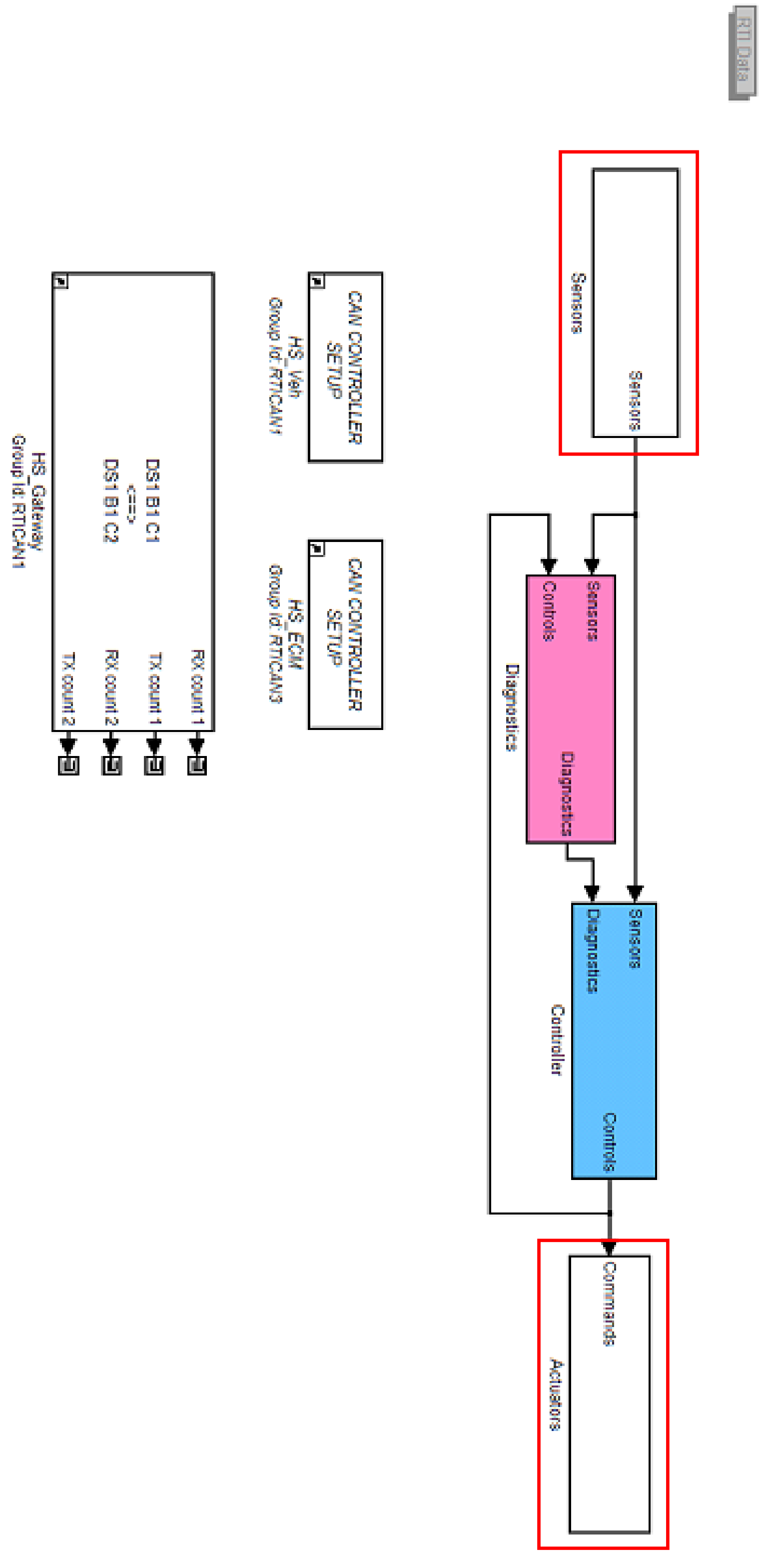


Figure 6-1. Supervisory controller model in MABXII

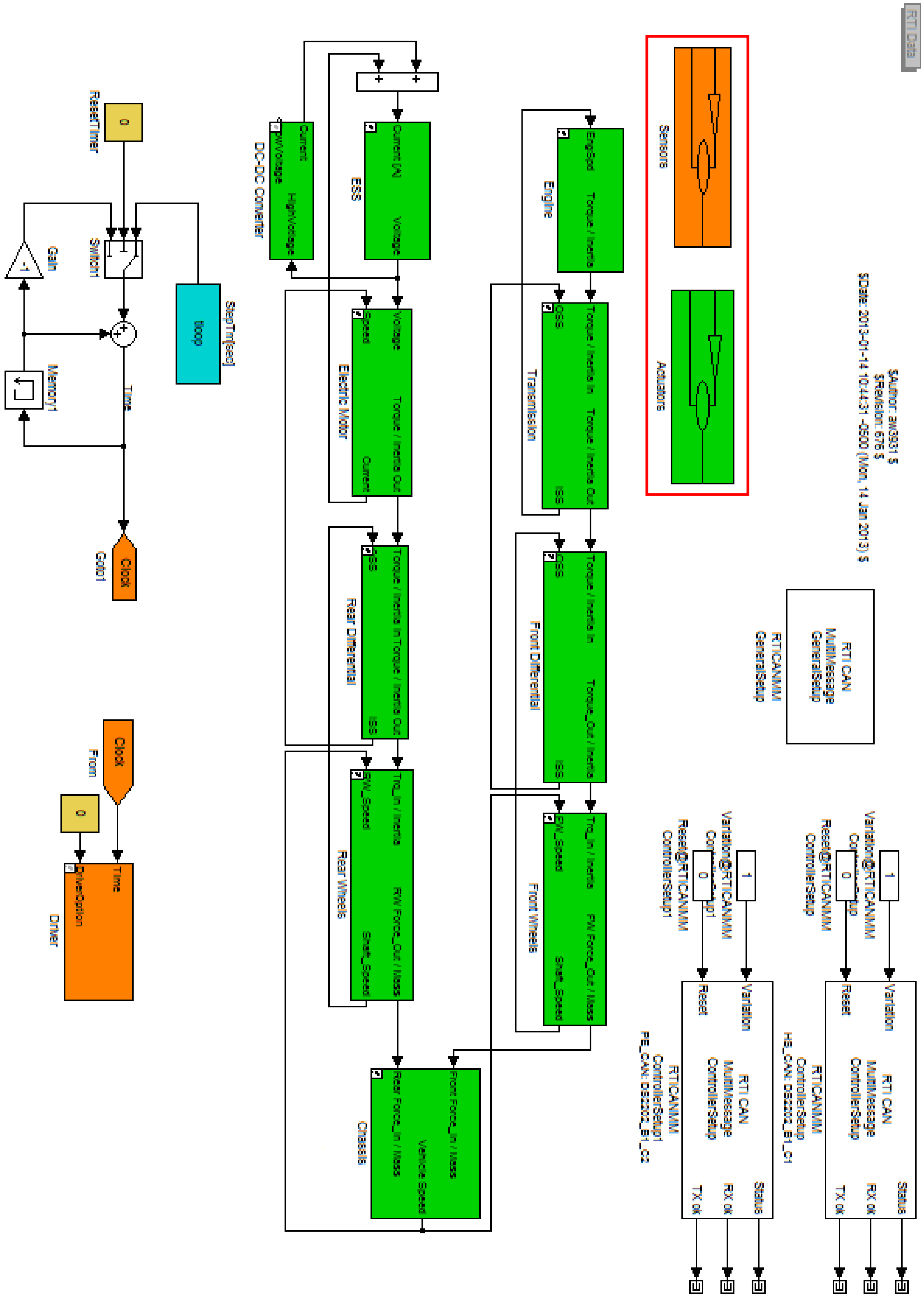


Figure 6-2. Vehicle plant model uploaded in HIL simulator

APPENDIX A. Summary of New Drivetrain Components Added to the Baseline Malibu [17]

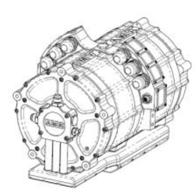
MicroAutoBox II, Vendor: dSpace, Delivered December 2011	
	
Dimensions	200 mm x 225 mm x 95 mm
Mass	Not specified
Operating Temperature	-40°C to +85°C (not under-hood rated, no cooling specified)
Power consumption	50W
Operating Voltage	6V-40 V (Supplied by 12V BUS)
Processor	IBM PPC 750 GL, 900 MHz
Analog Inputs	16 16-bit channels, 0-4.5 V, 5 mA max
Analog Output	4 12-bit channels, 0-4.5 V, 5 mA max
Digital I/O	40 inputs, 40 outputs (5mA), all channels fully configurable as frequency or PWM I/O
CAN Interface	Two dual CAN interface, 4 CAN channels in total
Serial Interface	2 x RS232
HV Battery 3P105S, Vendor: A123 Systems, to be delivered by summer 2012	
	
Dimensions (largest)	1280 mm x 700 mm x 210 mm
Mass	242.4 kg (estimated incl. packaging)
Nominal Voltage	340 V
Minimum Voltage	263 V
Maximum Voltage	378 V
Maximum Continuous Charge Current	60 A
Maximum Peak Charge Current	300 A
Maximum Continuous Discharge Current	180 A

Maximum Peak Discharge Current	600 A
Operation Temperature	-30°C to +50°C (liquid cooling required for given limits)
Interfaces (with ESS)	2-pin HV Tyco connector, 16-pin LV FCI connector, 2 coolant quick-release hose connectors.

HVH-250-090-S Permanent Magnet DC Brushless Motor, Vendor: Remy Motors, 3 units To be Delivered Mar. 2012

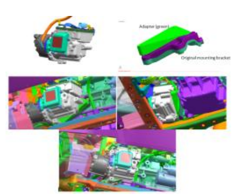
Dimensions (Cartridge only)	Diameter 310 mm x Height 244 mm
Mass	Cartridge 34 kg
Rotational Inertia	0.067 kg-m^2
DC BUS voltage	Up to 700 V
Peak Current (60 seconds)	300 Arms
Peak Power @ 340V, 2500RPM	82 kW
Continuous Power @ 340V, 2500RPM	60 kW
Peak Torque @ 340V, 2500RPM	320 Nm
Coolant inlet Temperature	Up to 90°C (ATF, Dextron XI)
Coolant flow rate	5 to 30 LPM
Interfaces	3 x M32 x 1.5 HV Phase connections, ITT CANNON MIL-DTL-38999 Low Voltage connector, SAE-8 O-Ring Boss coolant inlet and outlet.
Spline	Module 1.0, 24 teeth, Major Dia. 24.75/25.00, Minor Dia. 22.26/22.50, Pressure angle 30°

Dual Stack Motors Housing, Vendor: AMR, To be Delivered Aug. 2012



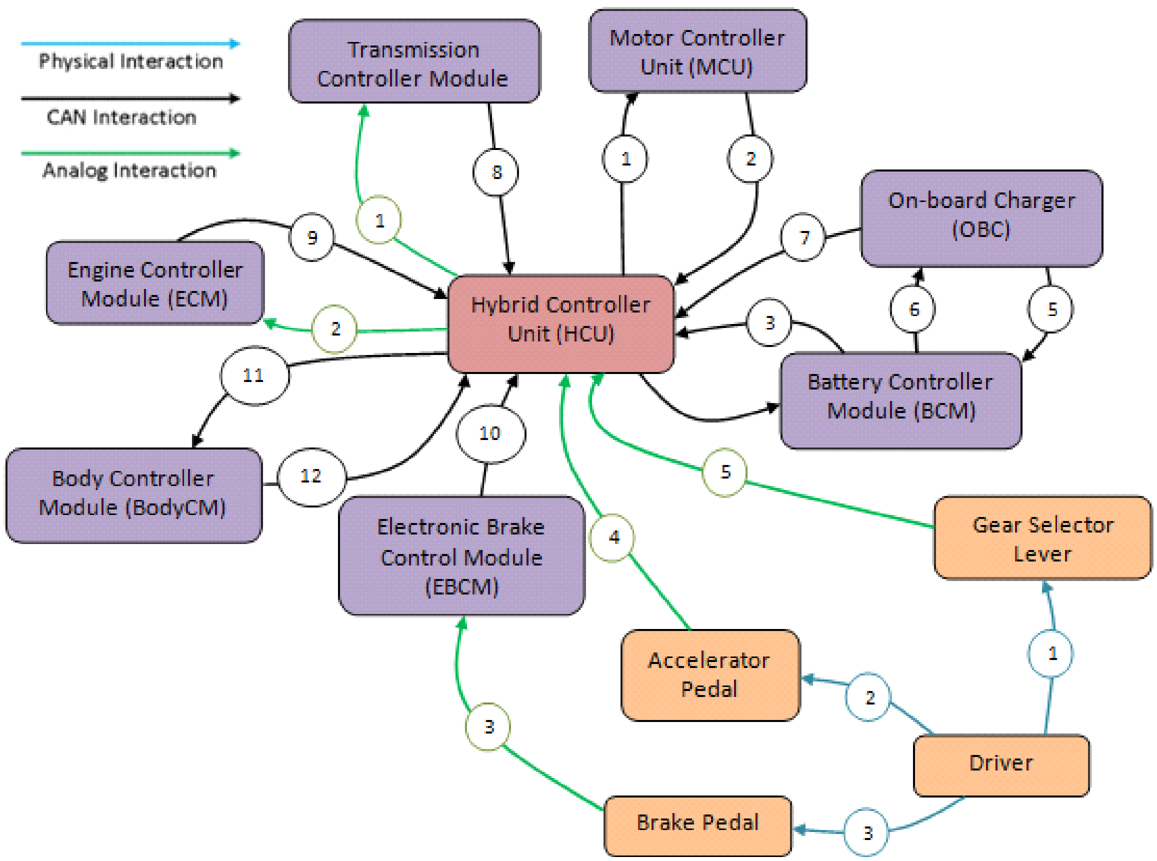
Dimensions	Length 492 mm x Height 350 mm x Width 300 mm

Mass (dry/wet)	30 kg / 35 kg
Coolant Flow Rate	10 LPM (WEG)
Interfaces	6 HV AC Phases connections protected by bolted cover. 2 LV connectors. ½” NPT WEG inlet and outlet
PM100DX Inverter, Vendor: Rinehart Motion Systems, Lead Time: 6 Weeks ARO	
	
Dimensions	314 mm x 200 mm x 85 mm
Mass	Not provided, estimated as 5 kg
Operating Voltage	100-360VDC (Maximum non-operational 500V)
Power Rating @ 300VDC	100 kW
Efficiency @ 300VDC	97%
Continuous Input Current	250 ADC
Peak Input Current	400 ADC
LV Power Supply	8-18 VDC
Operating Temperature Range	-30°C to +80°C (Water/Glycol cooling)
Coolant flow rate	12 LPM at rated power
Coolant port size	3/8” NPT standard
LV Interface	2x CAN2.0B compliant serial ports, RS-232 serial through 35-pin and 23-pin AMPSEAL connectors.
HV Interface	2 x 2 AWG wire recommended for DC side, 3 phases to AC side
Internal Capacitance	~500 µF
LE9 - 2.4L SI E85 Flex Fuel Engine, donated by GM, Lead Time: Unknown	
Dimensions (Overall incl. Transmission)	890 mm x 700 mm x 685 mm
Mass	140 kg
Inertia	0.1 kg-m^2 approximately
Peak power	131 kW
Peak Torque	230 Nm @ 5000RPM
MH8 – 6 Speed Automatic Transmission, donated by GM, Lead Time: with vehicle, expected summer 2012 (uses final drive with 4.11:1 ratio)	
Mass	87.5 kg
Input Shaft Inertia	0.003 kg-m^2

Gear Ratios	4.584, 2.964, 1.912, 1.446, 1, 0.746
Maximum Engine Power	134 kW
Maximum Input Torque	240 Nm
GM APM – 2.2kW DC-DC Converter, GM Donated, Lead Time: Unknown **No Picture**	
Dimensions	375 mm x 165 mm x 90 mm
Mass	5.5 kg
Efficiency	92% Typical
Input Voltage	260V-420 V
Output Voltage	12.5V-15.5 V (13.5 V Nominal)
Load Current	165A (max)
Operating Temperature	-40°C to +70°C (Air-cooled)
Interface	2 pins for HV In, 1 pin & enclosure for LV out, 2 CAN lines control and Run/Crank switched control
NLG513, Air Cooled On-Board Charger, Vendor: BRUSA, Lead Time: Unknown 	
Dimensions	334 mm x 263.5 mm x 88.5 mm
Mass	6.3 kg
Charging Voltage (full power)	200V-520 V
Current	12.5 A
Output Power	3.3 kW
GM Donated Mitsubishi HV ACCM. Lead Time: Unknown 	
Dimensions	253 mm x 200 mm x 195 mm
Mass	5.5 kg
Voltage Range	200V-440V (360V Nominal)
Current	15A Nominal, 25A @ 260V, 30A Peak
X Capacitance	25 µF +/-5%
Interface	HV Connector, LV Connector 8 pins, requires two

	CAN lines, Wake-up , Run/Crack and ground

APPENDIX B. A Complete Controller Interaction Diagram



The physical interactions between the controllers are as followed:

1. Driver operates gear selector lever
2. Driver operates accelerator pedal
3. Driver operates brake pedal

The CAN interactions between the controllers are as followed:

1. Enable inverter, motor torque command
2. Inverter enable status, motor actual torque, temperature and direction
3. Battery contactor status, voltage, current, max/min cell voltage and temperature, state of charge, buffer statuses

4. Contactor commands, vehicle wake or charge wake commands
5. OBC plug-in statuses
6. Current and voltage request
7. AC current in, DC current in, DC voltage out
8. Gear state, torque ratio
9. Engine ON/OFF status, actual engine torque, maximum torque, temperature, vehicle speed
10. Brake pedal applied pressure, ABS status, wheel slip status
11. Crank engine override
12. Key position status

The analog interactions between the controllers are as followed:

1. IMS signals to force transmission to neutral
2. Recast APP to engine for torque requests

APPENDIX C. WSU Complete VTS for Year-2 Final Competition [10]

#	Specification	Competition Design Target	Competition Requirement	WSU VTS Year 1	WSU VTS Year 2	WSU 4-Cycle Method	WSU On-road Method	WSU On-road Method + Trailer
1	Acceleration 0-60 mph	9.5 sec	11.5 sec	8.9 sec @ CD	10.2 sec @ CD			
2	Acceleration 50-70 mph (passing)	8.0 sec	10 sec	4.2 sec @ CD	5.1 sec @ CD			
3	Braking (60-0 mph)	143.4 ft	180 ft	174 ft	176 ft			
4	Highway Gradeability @ 20 min	3.5% @ 60 mph	3.5% @ 60 mph	13.52% @60 mph	11.2% @60 mph			
5	Cargo Capacity	16.3 ft^3	7 ft^3	> 10.83 ft^3	12.43 ft^3			
6	Passenger Capacity	>= 4	2	5	5			
7	MASS (GVW)	< 2250 kg	< 2250 kg	2245 kg	2205 kg			
8	Starting Time	< 2 sec	< 15 sec	Not Modeled	Not Modeled			
9	Ground Clearance	155 mm	> 127 mm	Not protruding beyond production	Not protruding beyond production			
10	Vehicle Range (< 10 gallon tank)	322 km [200mi]*	322 km [200mi]*	398.4 km [249 mi] @CS		403.8 km [251 mi] @CS	331.5 km [206 mi] @CS	290.9 km [181 mi] @CS
11	Charge-Depleting Range (CD)	**	N/A	57.12 km* [35.7 mi]		61.18 km [38 mi] UF = 0.6	68.04 km [42 mi] UF = 0.63	62.7 km [39 mi] UF = 0.61
12	CD Fuel Consumption (FC)	**	N/A	0		0	0	0
13	Charge-Sustaining (CS) FC	**	N/A	9.43 (lge/100km)* [840.7 Wh/km]		10.1 (lge/100km) [900.4 Wh/km]	12.23 (lge/100km) [1.09 kWh/km]	13.33 (lge/100km) [1.19 kWh/km]
14	UF-Weighted Fuel Energy Consumption (EC)	7.12 (lge/100km) [634 Wh/km]	N/A	3.96 (lge/100km)* [350.36 Wh/km]		4.04 (lge/100km) [360.17 Wh/km]	4.53 (lge/100km) [403.85 Wh/km]	5.20 (lge/100km) [463.58 Wh/km]
15	UF-Weighted	**	N/A	157.5		162.8	153.9	172.7

	AC Energy Consumption EC			(Wh/km)*		(Wh/km)	(Wh/km)	(Wh/km)
16	UF-Weighted Total EC	634 (Wh/km)	N/A	507.9 (Wh/km)*		523 (Wh/km)	557.8 (Wh/km)	576.6 (Wh/km)
17	UF-Weighted WTW Petroleum Energy (PE) Use	624 (Wh PE/km)	N/A	112 (Wh PE/km)*		115 (Wh PE/km)	129 (Wh PE/km)	148.3 (Wh PE/km)
18	UF-Weighted WTW GHG Emissions	204 (g GHG/km)	N/A	235 (gGHG/km)*		241 (gGHG/km)	271 (gGHG/km)	311 (gGHG/km)
19	Criteria Emissions	Tier 2 Bin 5	N/A	Not Modeled		Not Modeled	Not Modeled	Not Modeled

* Evaluated by using the EcoCAR2 combined "4-cycle" weighting method - EC2 E&EC Cycle

*** To meet the 200-mile range VTS, you will need to show at least 160 miles of range (200/1.25) based on measured DPG-Y on-road energy consumption with a trailer

APPENDIX D. DFMEA Results for Implemented Safety Algorithms

Line No.	Item / Function of the Part	Potential Failure Mode (Loss of Function or value to customer)	Potential Effect(s) of Failure	SEV	Potential Cause(s) / Mechanism(s) of Failure	OCC	DET	RPN	Recommended Action(s)
SC.3	Wheels	Wheels Slipping	Unintended Acceleration or Deceleration	10	ABS comes on when wheels are slipping, causing damage to wheels due to the addition of RWD.	5	3	150	Reduce motor and/or engine torque when wheel slip starting to occur to prevent ABS coming on.
SC.1	Safety Critical Modes	Unintended Acceleration	Compromise passenger's safety, crash	10	APP, motor, engine, wiring issues	2	6	120	Disable propulsion and slow vehicle down to a stop.
SC.5	Loss of CAN communi-cation with soft ECU	Incorrect HCU calculations etc.	Poor acceleration, mismatch between requested and actual torque.	10	Wiring problem with CAN, too much noise interference, wiring problems (shorts, open, intermittent)	4	5	200	Disable propulsion and slow vehicle down to a stop.
E2D2 .6	E2D2 Manager	Incorrect Engine & Motor trq coordination	Can cause accident, severe damage of vehicle components	9	Motor or Engine got stuck or detached from the load (shaft) while it is running. (electrical or mechanical fault)	1	7	63	Monitor the actual engine and motor torque to ensure that it matches the HCU torque requests. If it does not, derate accordingly to the amount of mismatch: Degrade, Limp Home or Shutdown

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ABSTRACT

SUPERVISORY CONTROLLER VALIDATION FOR A PLUG-IN PARALLEL-THROUGH-THE-ROAD HYBRID ELECTRIC VEHICLE BY SOFTWARE-IN-THE-LOOP TESTING

by

LOVE A. LOR

August 2013

Advisors: Dr. Jerry Ku

Major: Electrical Engineering

Degree: Master of Science

The goal of this research is to develop an operational supervisory controller for Wayne State University Hybrid Warriors' hybrid electric vehicle architecture that can be transitioned easily to a hardware-in-the-loop testing environment for the 2011-2014 EcoCAR2 competition. It serves to demonstrate how model-based design, specifically software-in-the-loop testing, is effective for the initial steps in design, verification, and validation of a supervisory control strategy. Overall, the supervisory controller aims to meet all safety and functional requirements while reducing fuel consumption. The thesis starts by presenting a plug-in parallel-through-the-road architecture and its powertrain hardware components. Next, characteristics and capabilities of all significant powertrain components are explained along with the implementation of the vehicle plant model. Initial stages and preparations for the development of supervisory controller begin with applying the "Design Failure Mode and Effects Analysis" and identifying the functional vehicle requirements. Control strategies implemented within the supervisory controller are discussed in detail. Finally, results from the software-in-the-loop testing as well as safety critical fault mitigation are shown, to demonstrate the end product of a supervisory

controller that has reached a high level of functionality and safety and therefore is ready for hardware-in-the-loop testing. Outlines are provided for extending the current work into next phases of hardware-in-the-loop testing, optimization using vehicle-in-the-loop results, and special applications such as cold-start.

AUTOBIOGRAPHICAL STATEMENT

Love Lor has been a student at Wayne State University since 2006, completing her Bachelor of Science in Electrical Engineering in 2010 and currently is completing her Master of Science in Electrical Engineering in 2013.

She joined the Wayne State University EcoCAR2 team in 2011 as the Controls team leader where she gained practical experience designing controls algorithms and performing model-based testing. She improved her organization and leadership skills by taking graduate classes, completing her internship at Michigan Gas Utilities, performing and directing Controls tasks as a Wayne State University Graduate Research Assistant and EcoCAR2 team leader and still have time to be the treasurer of the Hmong American Student Association all at once. It was a rewarding journey that contributed to her personal and academic growth as a student and she looks forward to the new opportunities that await her as she starts her career as an engineer at General Motors.