Development and Implementation of Control Strategy for A P4 Parallel Through-the-Road Hybrid Electric Vehicle

DEVELOPMENT AND IMPLEMENTATION OF CONTROL STRATEGY FOR P4 PARALLEL-THROUGH-THE-ROAD HYBRID ELECTRIC VEHICLE

BY

MATTHIEU ALISTAIR ORR, B.Eng.

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AUTHOUR:	Matthieu Alistair Orr
	B.Eng., (Mechanical Engineering)
	McMaster University, Hamilton, Ontario, Canada
SUPERVISOR:	Dr. Ali Emadi
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Lay Abstract

With hybrid electric vehicles and electric vehicles rising in popularity, the EcoCAR Mobility Challenge and its sponsors created an opportunity for McMaster University and 10 other universities across North America to modify a 2019 Chevrolet Blazer into a hybrid electric vehicle. This thesis focuses on the development of the control strategy for the McMaster University vehicle. A mathematical vehicle model was developed to run vehicle simulations in order to evaluate vehicle performance and the performance of individual components. Individual components were tested in order to develop control loops for these components. These control loops and other control modules were used during vehicle testing. On-road vehicle testing refined the vehicle control strategy evidenced by the over 1500km driven on public roads.

Abstract

The increasing demand for sustainable transportation solutions has led to the rapid evolution of hybrid and electric vehicles. This thesis, undertaken as part of the EcoCAR Mobility Challenge, presents the development and implementation of a control system for a P4 parallel through-the-road hybrid electric vehicle. A comprehensive vehicle model was developed using MATLAB Simulink. This model was used to model overall vehicle performance and component-specific performance throughout the EcoCAR Mobility Challenge and served as the foundation for the subsequent stages of control system development. Extensive component and vehicle testing formed the crux of this thesis. These bench tests provide invaluable data that aided in the implementation of the component control loops into the MAC Team vehicle. On-road vehicle testing further refined the energy management strategy, drivability, and charge sustaining of the high voltage battery. The vehicle control system has 10 control modules that successfully operated the MAC Team vehicle for over 1500km on public roads. The methodologies and findings can guide future projects aiming to optimize hybrid vehicle performance.

Acknowledgments

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Notations and Abbreviations

ACC	Adaptive Cruise Control
AVTC	Advanced Vehicle Technology Competition
BAS	Belted Alternator Starter
BASCM	BAS Control Module
BCM	Battery Control Module
CCM	Clutch Control Module
CAN	Controller Area Network
DOE	US Department of Energy
DOF	Degree of Freedom
EBCM	Electronic Brake Control Module
ECM	Engine Control Module
EEPROMS	Electrically Erasable Programmable Read-Only Memory
EM	Electric Machine
EMC	EcoCAR Mobility Challenge
EMM	Energy Management Module

EOP	Engine Operating Points
EV	Electric Vehicle
GIM	Gateway Interface Module
HEV	Hybrid Electric Vehicle
HIL	Hardware-in-the-Loop
HSC	Hybrid Supervisory Controller
HV	High Voltage
IBCM	Indicator Board Control Module
ICE	Internal Combustion Engine
LAN	Local Area Network
LUT	Look Up Table
LV	Low Voltage
MABx	dSPACE Microautobox 2
MARC	McMaster Automotive Research Center
MCM	Motor Control Module
MIL	Model-in-the-Loop
OCV	Open Circuit Voltage
OEL	Optimal Efficiency Line

PID	Proportional, Integral, Derivative
PSCM	Power Steering Control Module
RBCM	Regenerative Braking Control Module
SOC	State of Charge
TCM	Transmission Control Module
VIL	Vehicle-in-the-Loop

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Chapter 1

Introduction

Hybrid Electric Vehicles (HEVs) and Electric Vehicles (EVs) have emerged as pivotal innovations in the automotive industry. The market share of electric vehicles has tripled from 4% in 2020 to 14% in 2022, as sales exceeded 10 million electric vehicles sold in 2022. [1] The global push towards cleaner, more efficient, and more sustainable modes of transportation has led to this surge in the popularity of HEVs and EVs. Despite the significant growth and acceptance of HEVs and EVs, numerous challenges persist in their development and implementation. These include issues related to battery technology, charging infrastructure, vehicle range, and vehicle cost. The EcoCAR Mobility Challenge (2018-2022) is a student competition sponsored by General Motors, one of the largest automotive companies in the world, and the US Department of Energy. The competition involved 11 university teams who were tasked with modifying a standard gasoline-powered Chevrolet Blazer SUV into an energy-efficient hybrid electric vehicle. The challenge aimed to provide students with hands-on, real-world experience as they worked towards creating the automotive technology of the future. The competition is structured to resemble the real-world automotive product development cycle, challenging teams to test, prove and refine their work over four years. The McMaster University EcoCAR Team entered the EcoCAR Mobility Challenge as an experienced group of students having previously competed in the EcoCAR 3 competition (2014-2018), which tasked students with modifying a 2016 Chevrolet Camero while maintaining its iconic sports car characteristics.

For the EcoCAR Mobility Challenge the McMaster Engineering EcoCAR Team (MAC Team) decided, through careful analysis, to modify their gasoline-powered Chevrolet Blazer into a P4 parallel through-the-road hybrid electric Chevrolet Blazer.

1.1 Background and Motivation

1.1.1 EcoCAR Mobility Challenge

The EcoCAR Mobility Challenge (EMC) is the 12th engineering competition under the Advanced Vehicle Technology Competition (AVTC) series sponsored by the United States Department of Energy (DOE). The first AVTC competition began in 1988, titled the Methanol Marathon; the 1988 competition tasked universities with modifying a Chevrolet Celebrity sedan to operate on methanol. [2] In 2018 the EMC tasked universities with converting a 2019 Chevrolet Blazer, a fully gasoline-powered vehicle, into a hybrid electric vehicle. The 1988 competition, Methanol Marathon, had its number 1 goal to be an educational experience that teaches teamwork, planning, execution, and the need to problem solve. This creed continues with the EcoCAR Mobility Challenge. Students are incentivized to innovate while applying classroom knowledge to real-world applications. The EMC connects students with industry leaders through design feedback, problem-solving discussions, and mentorship. This competition has helped countless students break into the automotive and other industries as more experienced individuals. The EMC is a four-year-long competition, with each year having a different focus on vehicle product development.

- Year 1: Design
- Year 2: Component Testing & Integration
- Year 3: Full Vehicle Integration
- Year 4: Vehicle Controls Refinement

Year 1 is dedicated to design; the McMaster Engineering EcoCAR Team (MAC Team) conducted market research to determine the target market for the team's vehicle. The MAC Team determined that the target market for our vehicle was young city commuters. To accommodate the young city commuter, our team would operate as a car-sharing service. This service would allow users to locate a vehicle near them in a city setting, walk to the vehicle, get in, and drive to the user's desired location and just leave the car ready for the next vehicle user. The service was named MacShare, and a similar car share service, known as Zipcar, operates in over 500 cities across the United States and Canada; Figure 1 shows all the cities where ZipCar is available across the USA and Canada. [3]

Figure 1: ZipCar Location [3]

Target market research gives designers insight into the driving scenarios the vehicle will be exposed to. This allows designers to optimize toward the driving scenario the client is most likely to follow. The MAC Team determined that the average driving scenario a MacShare user will experience will be a dense urban driving scenario. Dense urban driving consists of high-volume deceleration and acceleration events. The MAC Team designed a P4 Parallel through-the-road hybrid electric vehicle, this design included components that would efficiently regenerative brake throughout a high-volume deceleration drive cycle and a smaller engine for the lower city speeds. These components were chosen for optimal fuel efficiency throughout a city rather than a highway performance vehicle.

Year 2 of the competition is dedicated to component testing and initial vehicle integration. Prior to vehicle integration, component functionality, component understanding, and component confidence must be established. During Year 2 the MAC team tested the YASA Electric Motor, Rinehart Motor Controller Inverter, the HEV4 High Voltage Battery, Valeo Belted Alternator Starter (BAS) and multiple controllers. The stock 2019 Chevrolet Blazer was stripped of its components, including the stock Internal Combustion Engine (ICE), in preparation for new components to be integrated. Upon its arrival, a new Internal Combustion Engine was integrated into the vehicle. ICE testing was performed to gain as much experience with this component as possible before the other components were integrated. By the end of year 2 all components had been tested and ready to be integrated into the vehicle.

Year 3 of the competition focused on full component integration and initial vehicle testing. Each component was integrated into the vehicle. Once the MAC Team vehicle had been fully integrated the initial vehicle testing began. This included testing start-up/ shutdown procedure of individual components and systems, ensuring each component communicates properly. Hybrid driving functionality was established at the end of year 3.

Year 4 was for control strategy refinement; the MAC vehicle had been fully integrated and had full control of its components. On road testing began, the vehicle control strategy was being refined for fuel economy and drivability. The MAC Team hybrid electric vehicle was able to drive for over 300km in a single day and accumulate over 1500km total from on-road testing.

1.1.2 Electrified Hybrid Powertrain Architectures

A hybrid electric vehicle is a type of vehicle that combines a conventional internal combustion engine system with an electrical propulsion system. This combination is referred to as the hybrid drivetrain, and the aim is to achieve better fuel efficiency than a conventional vehicle by lowering emissions and having increased range over fully electric vehicles. An HEV can take many forms in terms of its component placement within the vehicle, but the key components of a hybrid electric vehicle stay relatively constant, these components include:

- Internal Combustion Engine (ICE): Typical engine found in conventional vehicle that burns gasoline to generate power.
- Electric Motor (EM): Electric Motors use electricity to provide additional power to the vehicle. Reducing the workload on the ICE and thus improving fuel efficiency.
- Battery Pack: Stores electricity for the EM to utilize, the battery can be charged a few different ways based on the orientation of the HEV components. Some charging possibilities are through regenerative braking of the EM, battery pack charging through the ICE, or charging via plug-in while the vehicle is stopped.

- Transmission: A conventional vehicle transmission, some HEV configurations require the transmission to manage power from both the ICE and EM.

Hybrid electric vehicles have many different component orientations, each with a different benefit and purpose. The standard notation to differentiate these component orientations are P0, P1, P2, P3, P4.

P0 Hybrid Architecture

A P0 HEV architecture is the least reliant on the electric motor. The EM is attached to the ICE through a belt. The electric motor in this architecture is generally smaller and used to charge the low voltage battery and motoring capabilities, able to send additional torque to the wheels. This type of configuration is also known as a belt-alternator-starter system. Figure 2 shows the EM in pink attached to the ICE.

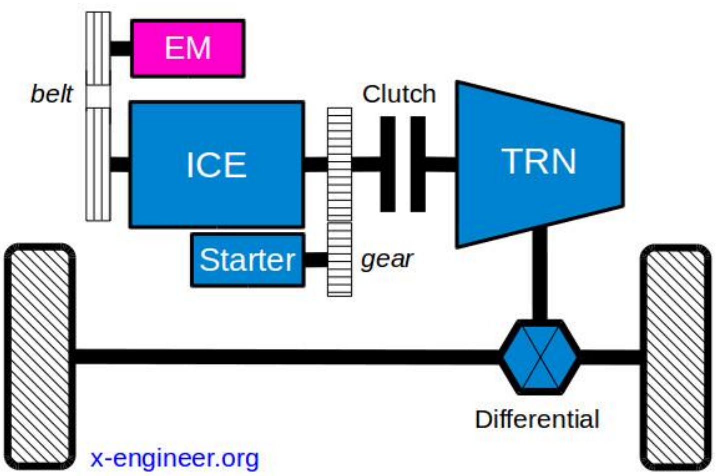

Figure 2: P0 HEV Architecture

P1 Hybrid Architecture

A P1 architecture is similar to a P0 by their coupling with the ICE. A P1 architecture directly connects an EM to the crankshaft between the ICE and transmission. The EM functions as a generator, motor and engine starter if needed. This architecture is an example of the ICE charging the High Voltage battery pack through the EM. When the clutch is open the vehicle will enter a full charging mode with this architecture but can never enter a full electric mode due to the electric motor's direct connection to the ICE. Figure 3 shows the EM in pink, located on the engine side of the clutch.

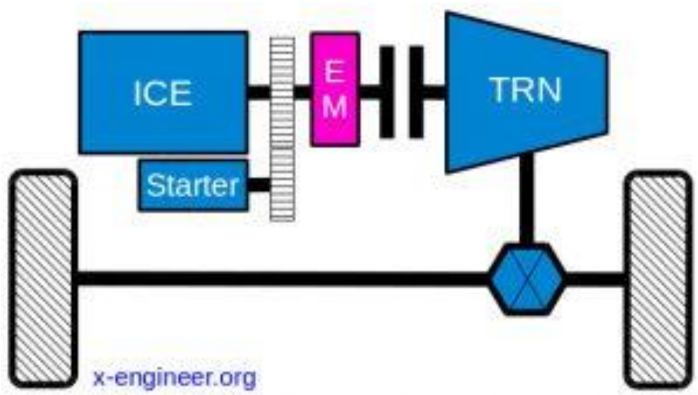

Figure 3: P1 HEV Architecture

P2 Hybrid Architecture

A P2 architecture has the EM coupled with the transmission rather than the ICE. A clutch separates the EM and transmission pairing from the ICE. This architecture allows for fully electric operation while the clutch is open and regenerative braking capabilities while decelerating with an open clutch. Figure 4 shows the EM located on the transmission side of the clutch.

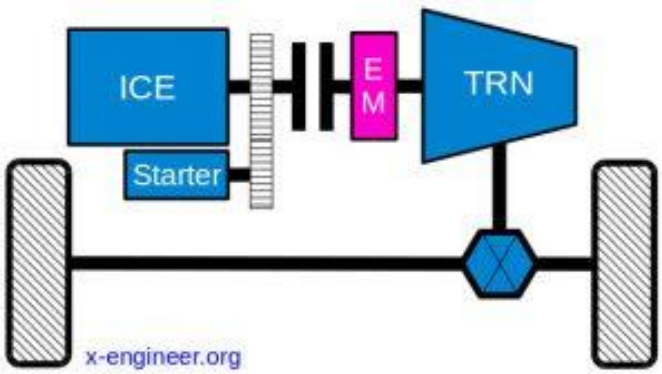

Figure 4: P2 HEV Architecture

P3 Hybrid Architecture

The P3 architecture has the EM located on the output shaft of the transmission. A clutch can be used once again to isolate the EM from the ICE and transmission. This configuration removes the transmission and EM coupling giving the vehicle only one speed when the EM operates in isolation, rather than a P2 architecture where the 9-speed transmission could be utilized. P3 is a less complex architecture for controls than P2 Architecture. Figure 5 shows the EM attached to the output shaft through a gear box rather than through the transmission. [4]

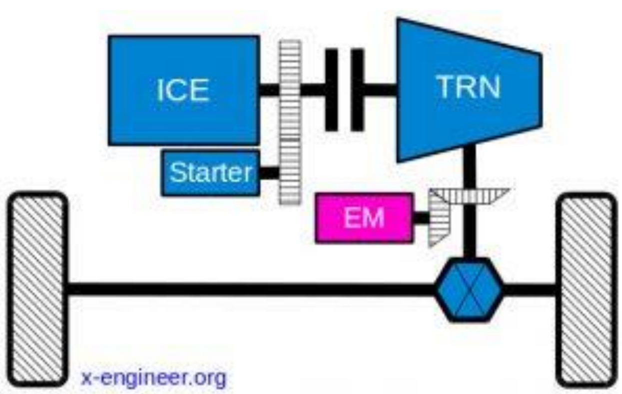

Figure 5: P3 HEV Architecture

P4 Hybrid Architecture

A P4 architecture is also known as a parallel through-the-road hybrid. This architecture utilized two disconnected powertrains, typically an ICE/Transmission powering the front powertrain and an EM/battery powering the rear powertrain. These two powertrains are connected by the wheels, through the road. This architecture is 4-wheel drive, and without slip, this means that the torque output of the front and rear wheels is added for a net torque on the vehicle. [5] This was the configuration the MAC Team designed in the first year of the EcoCAR Mobility Challenge. Figure 6 shows the P4 architecture configuration the MAC Team designed.

1.1.3 McMaster EcoCAR Architecture Definition

The McMaster Engineering EcoCAR Team designed a P4 Parallel Through-the-Road Hybrid Electric Vehicle with a P0 Belted-Alternator-Starter. Figure 6 shows the hybrid architecture the MAC Team designed for their Chevrolet Blazer.

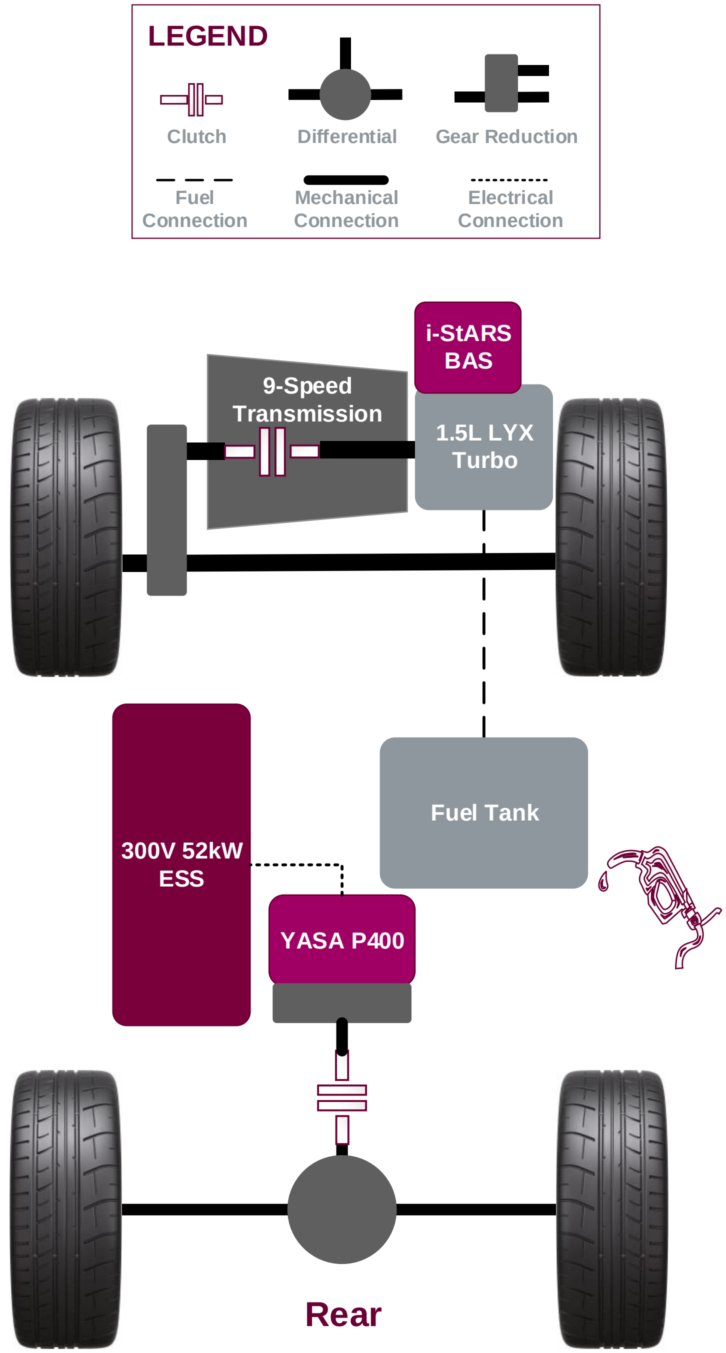

Figure 6: MAC P4 Parallel Through-the-Road Hybrid Architecture

The MAC team utilized the stock engine for the 2018 GMC Terrain an LYX 1.5L I4 ICE with a peak power of 119kW and peak torque output of 250 @ 2000-4000RPM, packaged in the same location as the stock Chevrolet Blazer 3.6L V-6 ICE data provided by General Motors. The 12V BAS was mounted in the same location as the production alternator, responsible for maintaining the low-voltage system. The BAS is capable of motoring at 6kW and generating at 3kW data provided by Valeo. The rear driveline includes a YASA P400 electric motor paired with a Rinehart motor controller inverter, a 4.6:1 single-speed gearbox, a clutch, and a Chevrolet Camaro differential. The YASA P400 is a 75kW permanent magnet motor capable of outputting 250Nm of torque continuously at 300V and a peak torque of 360Nm at 450A this data was provided by YASA. For a motor comparison, a 2016 Toyota Prius has a 53kW permanent magnet motor with a peak torque of 163Nm at 600V. A GM Malibu HEV4 pack was the high-voltage battery pack used by the MAC Team. The GM Malibu HEV4 is a 55kW high voltage battery pack with a capacity of 1.5kWh. The MAC Team implemented unique packaging of its rear driveline components. The EM, the gearbox and the clutch are packaged behind the rear axle, causing the differential to face the rear of the vehicle. Figure 7 shows the fully integrated MAC vehicle from under the vehicle. The silver motor and gearbox with red tape are packaged behind the rear axle to make room for the HV battery packaged as the black rectangular box and the silver fuel tank. In the EMC there were a total of 11 universities and the MAC Team was the only university that was able to package all of these components under the vehicle, all other university teams packaged the battery in the trunk. The stock fuel tank was so large that the MAC team could package a custom fuel tank alongside the HV battery.

Figure 7: MAC Team Vehicle Fully Integrated P4 Architecture

1.2 Thesis Objective

The objective of this thesis was to develop and implement a hybrid electric vehicle control strategy for the McMaster Engineering EcoCAR Mobility Challenge Team vehicle a modified 2019 Chevrolet Blazer and investigate the affect of this control strategy on the MAC Team's vehicle fuel efficiency and performance over a variety of drive cycles and tests. The work presented in this thesis was completed largely as EcoCAR Mobility Challenge deliverables or work completed to achieve competition objectives over a four year time frame. The contributions made as a result of these competition deliverables and objectives include:

1. The development of the MAC Team vehicle Matlab Simulink model used to evaluate initial MAC Team vehicle architectures and test different MAC Team vehicle control strategies within a model environment.
2. Multiple component test benches were set up to develop control loops the MAC Team components used in the modified 2019 Chevrolet Blazer. Components tested include the YASA P400 electric motor, Valeo iStARS belted-alternator-starter and the HEV4 high voltage battery pack.
3. Vehicle testing was conducted to evaluate component performance within the MAC Team vehicle and ensure reliability for on-road vehicle testing.
4. On-road vehicle testing results were used to analyse the vehicle control strategy implemented in the MAC Team vehicle.

1.3 Thesis Outline

The remainder of this thesis will be structured as follows. Chapter 2 presents the MAC Team vehicle model, describing the modified 2019 Chevrolet Blazer architecture. The MAC Team vehicle model was used to test different vehicle control strategies and evaluate the vehicle performance in a simulated environment. Chapter 3 describes the testing performed on the new MAC Team components; these test benches were used to gain understanding of how to control each component. Initial in vehicle component testing is described in chapter 3 to confirm component control once integrated into the vehicle. Chapter 4 delves into the MAC Team vehicle control system, describing the vehicle torque split calculation between the engine and motor. There are 10 control loops described in chapter 4 that make up the vehicle control system. The performance of the MAC Team vehicle is evaluated in chapter 5. The MAC Team vehicle's performance is evaluated over four unique driving conditions. Chapter 6 concludes the thesis with a thesis summary and the future work required to improve the current MAC Team vehicle control strategy.

Chapter 2

Vehicle Model Development for Control Strategy Simulation

A vehicle model is a mathematical representation of a vehicle's systems and components used to assess vehicle and component performance over a set driving cycle. Effective modeling gives engineers the ability to compare the performance of different designs and optimize their designs. An accurate model requires real-world validation and real-world data. Real-world data can be acquired for individual components by performing component testing or from manufacturer-supplied data and specifications. A vehicle model consists of a powertrain model, a vehicle dynamics model, a control system model, and a driver model. A powertrain model includes an engine, transmission, electric motor, and a high-voltage battery pack. A vehicle dynamics model involves vehicle braking systems, interactions between the ties and the road surface, vehicle specifications, including the center of gravity and mass of the vehicle. The control system model includes models of electronic and software-based systems that control various aspects of the vehicle's performance, including engine and electric motor torque split strategies, transmission controls, and battery management. The driver model sends acceleration and deceleration pedal positions to the control system based on the current driving scenario. By simulating and analyzing these models, engineers can identify design issues, optimize performance, and validate the functionality of the vehicle's systems and components. This can reduce development time, reduce cost, improve design quality, and increase final product reliability. [6]

At the beginning of year one of the Ecocar Mobility Challenge, MathWorks sponsored a Matlab Simulink Model of a stock 2019 Chevrolet Blazer. The MAC Team converted the stock Chevrolet Blazer architecture model into a P4 parallel through-the-road architecture. This MATLAB Simulink model of the MAC Team vehicle was utilized every year of the EMC.

2.1 MATLAB Simulink Overview

MATLAB Simulink is a graphical programming environment for modeling, simulation, and analyzing dynamic systems. Simulink provides an interactive, block diagram-based interface that allows engineers to build and simulate complex systems by connecting functional blocks representing various components, subsystems, and control systems. Simulink has an extensive library of pre-built blocks and functions to create vehicle models. [7]

2.1.1 V- Model Development

The V-model is a system development methodology used by the MAC Team to develop the MAC Team vehicle and its model. The stages of this methodology take the shape of a "V." The V-model can be used to structure the development process of complex system, using MATLAB and Simulink tools. The V-model development process typically consists of the following stages. Figure 8 shows the stages in the V shape. [22]

1. Systems requirements definition: Engineers define the system's high-level functional and performance requirements. This can include high-level requirements; the MAC Team Vehicle must accelerate from 0-100km/h in less than 9 seconds or lower-level control

requirements; the Motor Control Module (MCM) shall enter a start-up state when high voltage is detected.

2. Systems Architecture and Design: Engineers develop overall system architecture and create detailed designs for each subsystem. Designing for the flow of information within the systems architecture.
3. Subsystems and Component Design: Engineers design and test individual subsystems and components. Simulink provides libraries of pre-built blocks and functions that can be used to create models of many subsystems and components.
4. Component Implementation: Engineers implement subsystem and component design, typically using a combination of hardware and software components. MATLAB and Simulink support code generation, enabling engineers to automatically generate code for their designs that can be deployed on embedded systems or hardware.
5. Integration and Verification: Engineers integrate the subsystems and components to create the complete system and verify that it meets the specified requirements.
6. Validation and Testing: The complete system is validated and tested to meet the defined requirements and performance criteria.
7. Operation and Maintenance: Once the system is deployed, MATLAB and Simulink can support ongoing operation and maintenance tasks, such as data analysis, diagnostics, and system optimization.

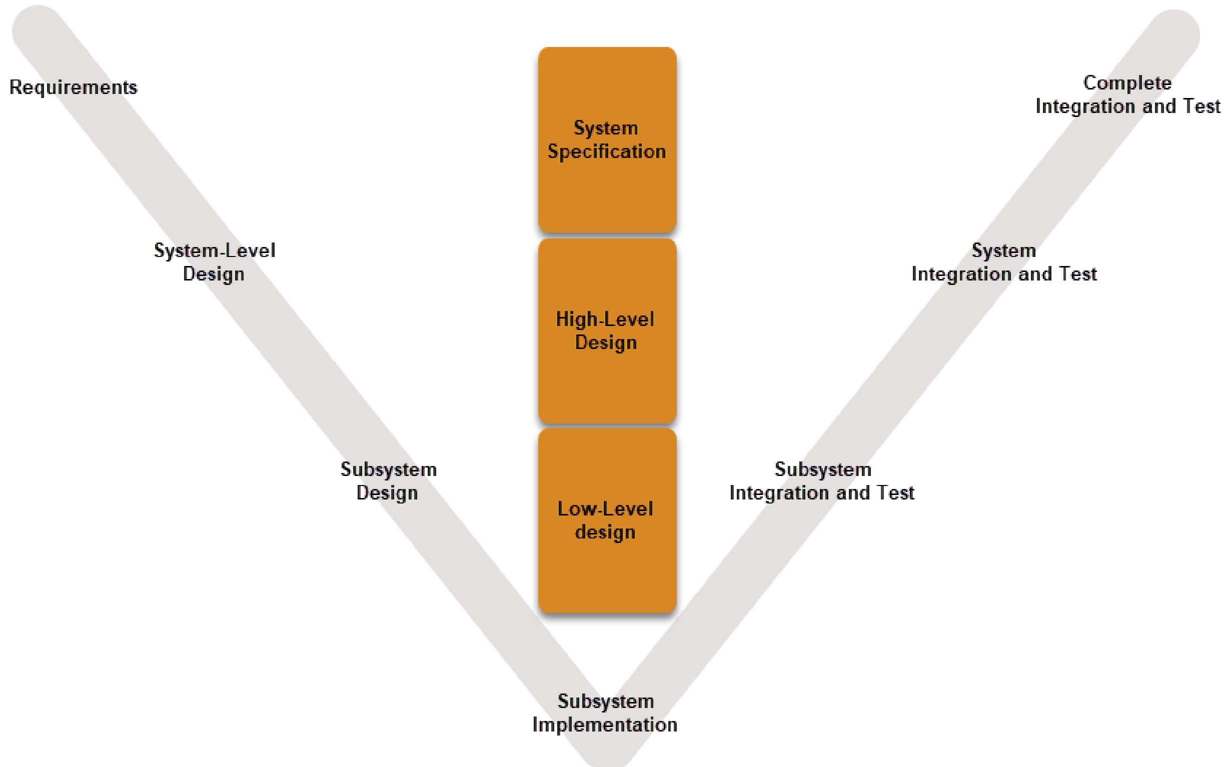

Figure 8: V-Model Development

2.1.2 Model-in-the-Loop and Hardware-in-the-Loop

Model-in-the-Loop (MIL) and Hardware-in-the-Loop (HIL) are testing, and validation methodologies used during the development of the MAC Team vehicle. These methodologies are used in conjunction with V-Model development. MIL is used to simulate control algorithms and plant models within a virtual environment. MIL testing can validate the functionality and performance of a control algorithm before implementing it in hardware. HIL involves the use of a physical prototype of the system to test control algorithms. HIL simulation tests the interaction between the control algorithms and the actual components of the system. HIL testing of individual components prior to system integration is crucial. Gaining knowledge of an individual component's functionality leads to higher confidence when components are integrated into the larger system. [8]

2.2 MAC Team Modified 2019 Chevrolet Blazer Model Overview

There are two frameworks in which vehicle models operate. A torque forward framework or a torque backward framework. Torque forward calculates torque from the power sources to the wheels, based on driver inputs. Torque calculated at the power sources, ICE and EM, propagates through the drivetrain components to the wheels. The torque forward framework takes inputs such as accelerator pedal position, engine speed, and battery voltage to compute the resulting torque at each subsequent component (Transmission, Differential, Clutch, etc.) until the torque reaches the wheels. The advantage of the torque forward framework is that it simulates a real driving experience, where a driver determines component torque output through a controller, this allows for control strategy testing within the torque forward framework. The torque backward framework first determines the required torque at the wheels to achieve a certain vehicle performance (Acceleration, constant speed, or deceleration). Then it works backward through the drivetrain components to calculate the required torque at the power sources. Torque backward does not require a driver model and provides more accurate insight into a powertrain system's ability to achieve specific performance goals.

The MAC Team vehicle model follows the torque forward framework with a driver model, controller model, powertrain model, and vehicle dynamics model. Figure 9 shows the top layer of the MAC Team 2019 Chevrolet Blazer Simulink model. The drive cycle block on the right feeds to the driver model. The controller block in the middle receives driver model signals, environment signals, and vehicle feedback data. The vehicle plant model block takes environment data and controller signals and outputs vehicle feedback data that is set to the driver, controller, and visualization block.

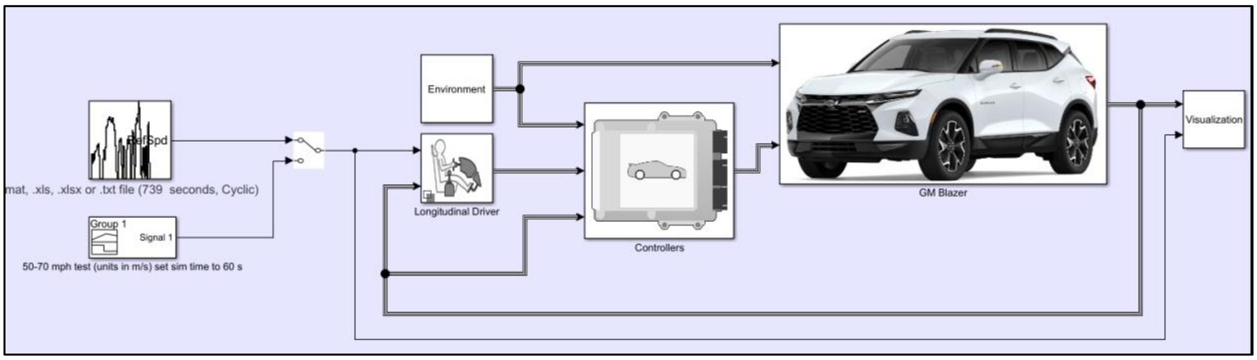

Figure 9: Top Level of MAC Team Vehicle Matlab Simulink Model

2.2.1 Driver Model

The driver model operates similarly to a PID controller with current speed and desired speed as its inputs and acceleration pedal position and deceleration pedal position as its outputs to achieve the desired speed of the model vehicle. A pre-built driver model block was used titled “Longitudinal Driver Model” with driver reaction time and driver preview distance as input parameters. The values chosen for simulations were a driver reaction time of 0.25 and a preview distance of 200m, which is based on a driver’s ability to see red or green lights ahead. [9] [10]

2.2.2 Hybrid Supervisory Controller Model

The Hybrid Supervisory Controller (HSC) is separated into five layers, the input layer, input conversion layer, application layer, output conversion layer, and output layer. The input layer consists of driver, vehicle, and component feedback information. Each signal has its units tracked from the input layer. The conversion layer takes input layer data and converts it to a form that is easier to use in the application layer; for example, the transmission sends its current gear (1-9), the conversion layer takes the gear number and outputs the gear ratio which can be used in the application layer. The application layer includes the energy management strategy for determining component torque requests based on driver inputs and feedback signals. The output conversion layer converts signals from the application layer into proper units for the vehicle model. Safety checks are performed in this layer, checking if torque requests are within component limits. The output layer organizes all the signals into signal buses and are sent to the vehicle model or to the visualization block for diagnostic purposes.

2.2.3 GM Blazer Plant Model

The vehicle plant model is responsible for mathematically modeling the various components within the vehicle. This includes models for the engine, transmission, differentials, gearboxes, shafts, electric motors, and high and low-voltage systems. The vehicle plant model receives torque requests from the HSC block, and the mathematical models for each component calculate a resulting torque and calculate feedback information including component speed, vehicle speed, voltage, state of charge (SOC), and fuel efficiency of the vehicle. The vehicle plant model is split into three models, the engine model, the electrical plant model, and the drivetrain model. The electrical plant models the high and low-voltage systems in the vehicle. The drivetrain models the power-transmitting mechanical components, clutches, gearboxes, and transmission.

2.2.4 Engine Model

The internal combustion engine model utilizes a pre-built Simulink block titled “Mapped SI Engine” to characterize the Engine and the catalytic converter. This block takes many input parameters that are engine-specific maps and specifications, such as the number of cylinders, torque vs. speed breakpoint maps, efficiency maps, and emissions data. All engine-specific data was supplied by General Motors and MathWorks. Commanded torque, and engine speed are input variables into a Look Up Table (LUT) that determines the engine output torque. The engine’s output torque is used as an input into another LUT that determines the engine’s speed, fuel flow rate, emissions, and other engine data. These outputs are valuable when analyzing the MAC vehicle performance over different drive cycles. Figure 10 shows the Mapped SI Engine block within the MAC Team vehicle plant model. [11]

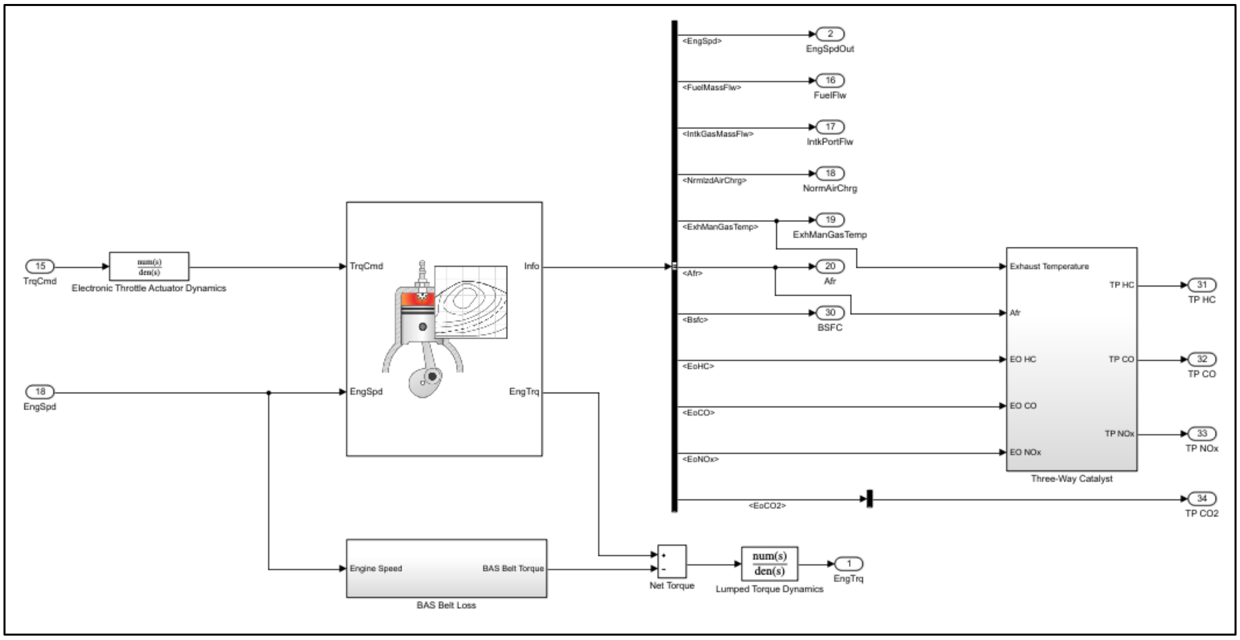

Figure 10: ICE Model Including BAS Losses

The Valeo belted alternator-starter is belted to the engine, and the added resistance is interpreted as torque losses subtracted from the engine's output torque. Based on data from Valeo, the belt losses are constantly 3 Nm multiplied by the belt ratio of 2.81 for a total loss of 8.43 Nm. Figure 10 also shows the BAS Belt Loss block below the engine block.

2.2.5 Electrical Plant Model

The electric plant contains models for all the MAC Team vehicle's high and low-voltage electric systems. These systems include the YASA P400 Electric Motor, the HEV4 Malibu high voltage battery pack, the Valeo i-StARs BAS, low-voltage (LV) loads, and the LV Battery. The "Mapped Motor" Matlab pre-built block was used to model the YASA P400 Electric Motor and the Valeo i-StARs BAS motor. The input parameters for this block include a tabulated torque-speed envelope and a motor efficiency map. For the YASA P400 Electric Motor, the MAC Team gathered parameters through motor dyno testing performed at the McMaster Automotive

Research Center (MARC) during the EcoCAR 3 competition. Through motor dyno testing, the MAC Team determined the toque-speed envelope and the motor's efficiency leading to improved model accuracy and confidence. The YASA electric motor is symmetrical regarding its power output. The YASA electric motor is able to motor and generate at the same specification. The Valeo i-StARS BAS is asymmetrical regarding its motoring and generating capabilities. The BAS can provide a maximum of 2.3kW of motoring and 4kW of generation. The Valeo i-StARS model uses the same mapped motor block, requiring torque-speed envelope and the efficiency map. Due to the asymmetrical power behavior of the Valeo i-StARS, two mapped motor blocks were used to represent one motor, alternating between the blocks based on generating or motoring. Valeo provided the BAS power data, torque-speed envelop, and motor efficiency. Figure 11 shows the two different "Mapped Motor" blocks used to represent the motor and generation operation modes of the BAS.

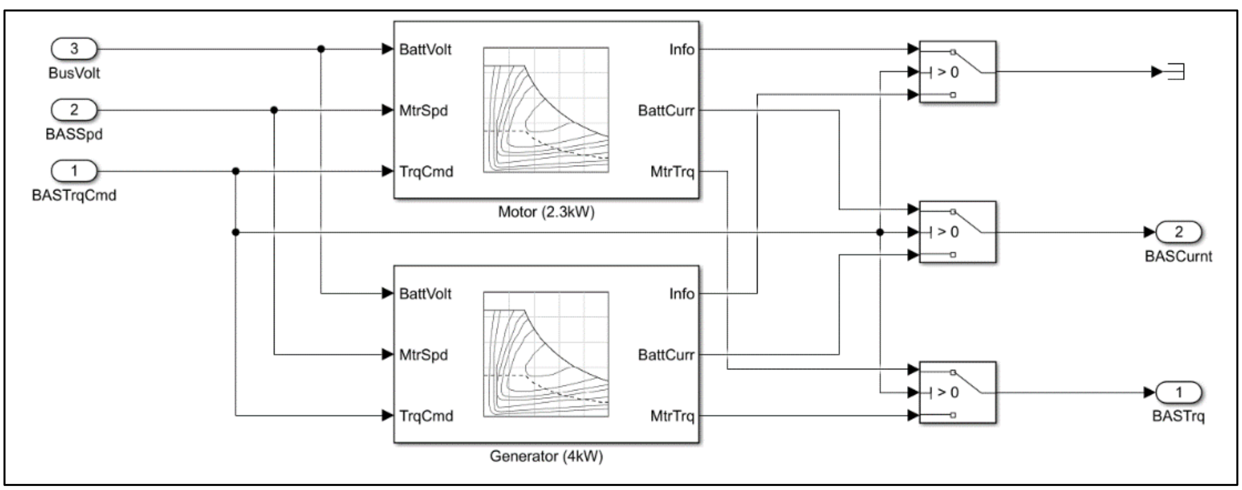

Figure 11: BAS Model

The "Mapped Motor" block, used to model the YASA and the BAS, calculates the output torque and the electrical current draw required to output this motor torque. The electrical current, I_{Batt}, is calculated by dividing the motor's mechanical power by the battery voltage, V_{Batt}, and the motor's efficiency, η. Motor mechanical power is calculated by multiplying motor speed, ω_{Mot}, and motor torque, T_{Mot}. This equation is the same for motoring and generating, the motor pulls current from the battery or generates current for the battery. [12]

Equation 1: Motor Current Drawn Calculation

$$I_{Batt} = \frac{T_{Mot} * \omega_{Mot}}{\eta * (T_{Mot}, \omega_{Mot}) * V_{Batt}}$$

The high-voltage battery pack is modeled using the "Datasheet Battery" block, which is used to model Lithium-ion batteries based on manufacturer datasheet parameters. This block utilizes an Open Circuit Voltage curve (OCV-SOC) and internal resistance data of the battery to model the GM Malibu pack. All high-voltage battery pack parameters were provided by GM. [13]

A Lead-Acid low voltage battery is modeled using the pre-built Matlab block "Equivalent Circuit Battery". This block allows for more detailed simulation data utilizing open-circuit voltage (OCV), series resistance and parallel Resistance-Capacitance (RC) branches. The BAS is why a more complex model was chosen for the LV battery. The BAS was intended to aid with start/stop, torque assist, and generate for the LV system. This activity level on a low-voltage system required a more detailed view of the battery performance through a drive cycle. A constant load was also put onto the low voltage battery to consider the MAC Team's added controllers, fans, and pumps. [14]

The I_{Batt} variable used in Equation 2, is calculated within the mapped motor block governed by Equation 1. Showing the interconnectedness of these two blocks.

Equation 2: Terminal Voltage Calculation

$$V_T = OCV(SOC) - V_0 - V_1$$

$$V_0 = I_{Batt} * R_0$$

$$V_1 = \int \frac{I_{Batt}}{C_1} - \frac{\widetilde{V_1}}{R_1 * C_1} dt$$

2.2.6 Drivetrain Model

The engine and electrical plant models output component torque to the drivetrain model. The engine model transmits torque to the torque converter automatic 9-speed transmission, from the transmission to the front differential, through the axle to the wheels, and the resulting force on the vehicle is determined. The motor model transmits torque to a single-speed gear reduction, through a clutch, through the rear differential, through the axle to the wheels, and the resulting force on the vehicle is determined. A mathematical model was developed for each of these mechanical components.

2.2.7 Transmission Model

The transmission models couples two pre-built blocks, the “Torque Converter” and the “Ideal Fixed Gear Transmission.” The “Torque Converter” block models a fluid coupling device commonly used in automatic transmissions. It transmits torque from the engine to the transmission while allowing variable speed ratios. The torque converter block has three mechanical connections, the pump (input) connected to the engine, the turbine (output) connected to the transmission, and an optional stator connection. The block simulates the torque converter’s performance using impeller capacity, stall speed ratio, and peak torque multiplication ratio. These torque converter parameters were supplied by GM. Figure 12 shows the coupling of the torque converter and transmission within the MAC Team vehicle model. [15]

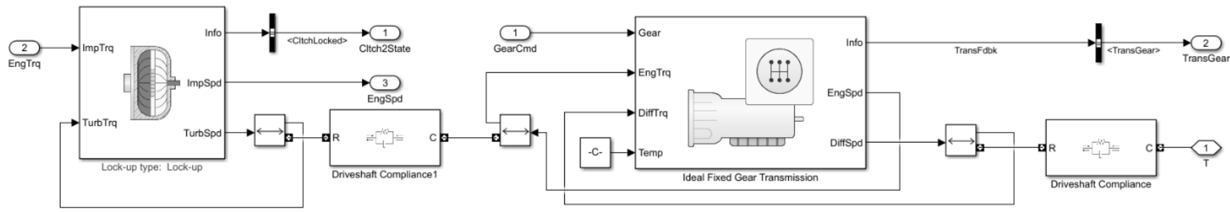

Figure 12: Torque Converter and Ideal Fixed Gear Transmission within Transmission Model

The “Ideal Fixed Gear Transmission” block models a simplified lossless gear transmission. It assumes there are no losses due to friction or inertia. This block has two mechanical connections, the input is connected to the torque converter, and the output is connected to the differential. The block multiplies the input torque by the current transmission gear ratio and outputs this torque to the differential. The transmission gear changes based on the transmission control module located in the application layer of the hybrid supervisory controller. The transmission control module calculate gear shifts based on accelerator pedal position and speed thresholds. Gear shifting schedules output the speed thresholds for gear shifting. GM and MathWorks supplied this control module. [16]

2.2.8 Differential Model

The front and the rear differential are modeled using the “Open Differential” pre-built block. This block models the gear system that splits the input torque and speed between two output shafts. Parameters such as gear ratio, inertia, and damping are used in this model and are supplied by GM for both differentials used. [17]

2.2.9 Single Speed Gear Box

The single-speed gearbox in the rear takes torque inputs from the motor. The pre-built block "Gearbox" was used to model this component. The "Gearbox" block operates as an ideal fixed gear coupling assuming no losses due to friction. The physical gearbox, installed into the MAC Team vehicle, was designed by a McMaster graduate student, and this student supplied parameters such as damping and inertial. The gear ratio for this gearbox was chosen by running full model simulations over a city drive cycle to determine the optimal gear ratio for improved motor efficiency. [18]

2.2.10 Disc Clutch Model

The clutch in the rear separates the motor and gearbox from the rear differential and is modeled using the "Disc Clutch" pre-built block. This block models the friction between the clutch plates when they are pressed together by actuator force. The friction force is determined by the clutch pressure, the friction coefficient, and the clutch plate contact area. When the clutch is fully engaged, the input and output sides rotate at the same speed, allowing torque transmission. When the clutch is disengaged, torque is not transmitted through this block. Parameters such as static, dynamic friction coefficients, clutch plate contact area, and maximum actuator force are required. Tilton, the manufacturer supplying the MAC Teams rear clutch, supplied these parameters. The open and close clutch requests are sent from the clutch control module located in the application layer of the HSC seen in Figure 13.

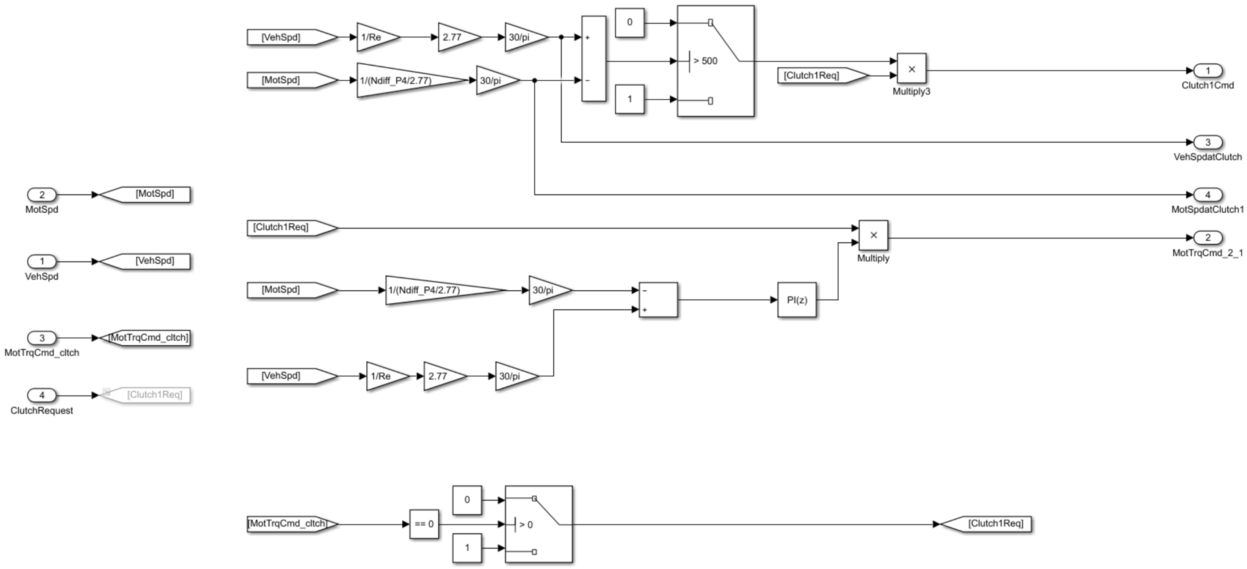

Figure 13: Motor Speed Match Calculation and Close Clutch Request

The default position of the clutch is open. When a motor torque is requested, a close clutch signal is sent to the clutch control module. The motor cannot output torque until the clutch has been closed. For the clutch to close, the motor side of the clutch must match the speed of the wheel side of the clutch. This speed match is necessary to increase driver comfort and decrease component damage. The speed matching in this model is not as simple as sending a speed signal to the motor model. This model is a torque forward model, meaning torque requests must be used to achieve a set speed. This can be achieved using a PI Controller. The PI controller outputs a motor torque request that attempts to match the clutch plate speeds. When the difference in speed is within a set threshold, a clutch close request is sent to the disc clutch model. [19]

2.2.11 Wheels, Brakes, and Vehicle Dynamics Models

The front and rear wheels are modeled using the pre-built "Longitudinal Wheel" block. This block captures the interaction between the wheel and the road surface, considering the tire's longitudinal force, rolling resistance, and slip. This model has two main connections, the mechanical connections between the wheels and the drivetrain components and the physical connection between the wheels and the road governed by the vertical load acting on the tires due to the vehicle's weight. The parameters needed for this block are tire radius, inertia, slip force, and rolling resistance. These parameters were supplied by GM. [20] The wheel model output a front and rear axle force which is sent to the "Vehicle Body 1DOF Longitudinal" block which represents the longitudinal dynamics of the vehicle body. This block considers aerodynamic drag, road grade, and tire-generated forces to output vehicle velocity. Parameters required for this block include vehicle mass, aerodynamic drag coefficient, reference area, and center of gravity. Parameter were provided by GM and through MAC Team analysis of the vehicle. [21] Figure 14 shows the free body diagram that governs the "Vehicle Body 1DOF Longitudinal" block.

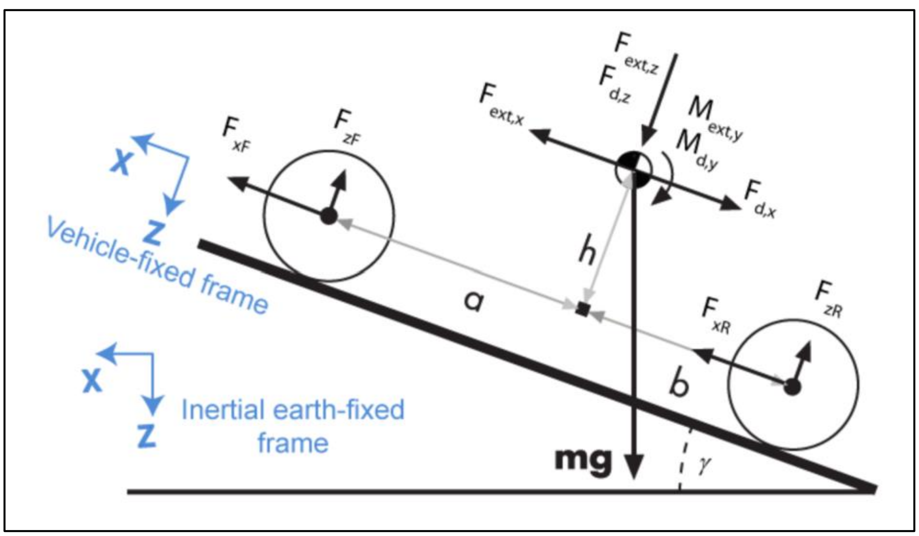

Figure 14: Free Body Diagram That Governs "Vehicle Body 1DOF Longitudinal" Block

2.3 Model Confidence

The MAC Team vehicle model uses real-world test data or direct manufacturer data to populate most parameters within the model. All General Motors component parameters were supplied to the MAC Team. Valeo and Tilton supplied parameters for the BAS and rear clutch. The YASA data was acquired through motor dyno testing. Using this type of data in a vehicle model can lead to more accurate simulations, but a vehicle model will never be 100% accurate in simulating every component and vehicle performance. Understanding a model’s limitations is extremely important when using simulation results to make decisions about vehicle design. The highest model confidence can be achieved through model validation, and validation requires your model to be compared to a real world prototype. Comparing real world vehicle data to model data allows engineers to learn about both the model and the vehicle itself. When the MAC Team vehicle model is compared to the real-world logs of the MAC Team vehicle, there are many similarities in component performance and many differences. Understanding the differences and similarities contextualizes the outputs of a model allowing engineers extract useful information from a model even if it is not 100% accurate. The MAC Team model was developed in the first year of the EMC with help from General Motors and MathWorks but there was not a vehicle to validate the model until year 4. The model was continually updated when new information was acquired through testing, using component test data from test benches or altering the model control system to better reflect the way the vehicle control system operates.

2.4 Summary

This chapter focused on the MCA Team vehicle model used to assess vehicle and component performance over a set of drive cycle. Effective modeling allows engineers to compare the performance of different control strategies and power train configurations without the need for a physical prototype. This chapter provides an overview of MATLAB Simulink a software used for simulation and model-based design. The MAC Team vehicle model uses a torque forward framework with a driver model, controller model and vehicle plant model. This chapter underscores the significance of vehicle modeling in the development and implementation of control strategies for hybrid electric vehicle.

Chapter 3

Component and Vehicle Testing and Control System Implementation

The MAC Team components, discussed in section 1.3, were required by the team to be individually tested prior to installation into the vehicle. The MAC Team tested the Valeo i-StARS BAS, the Malibu HEV4 High Voltage battery pack, and the YASA P400 electric motor coupled with the Rinehart Motor Controller Inverter. Testing allows engineers to confirm that each component functions as expected under a variety of conditions. The MAC Team vehicle's main controller, the dSPACE Microautobox 2 (MABx), was utilized during component testing to ensure a smooth transition from individual component testing to in-vehicle testing. The MAC Team performed chassis dynamometer testing. This chassis dynamometer testing allowed the MAC Team to test at set speeds for long testing section in a safe environment. This testing led to the MAC Team establishing torque control of the engine. Having torque control of the engine allowed the MAC Team to begin a torque split strategy between the ICE and the YASA electric motor. Many control loops developed for each bench test were used as the building blocks for the component control loops found in the final MAC Team vehicle.

3.1 Component Communication Methods

3.1.1 CAN Communication

Controller Area Network (CAN) is a robust vehicle communication bus standard, designed to allow controllers and devices to communicate with each other within a vehicle without a host computer. CAN communication is a message-based protocol. CAN messages are broadcast to a network of devices not sent to specific individual devices. Each message contains an identifier. Each device uses the message's identifier to determine whether the message is relevant to them. This approach ensures that all devices are kept informed of the network's state and can respond accordingly. CAN has mechanisms for error detection and signaling. If a device detects an error in a message, it can signal this to other devices on the network, which can take appropriate action. This helps to ensure the reliability of the network. CAN is used in various applications within a vehicle, from controlling windows and mirrors to engine management and brake control. CAN was used as the main form of communication in every MAC Team component test. Figure 15 shows the wiring of a CAN bus. Two wires, a CAN High wire (CANH) and a CAN Low (CANL). CANH and CANL connect all the devices and controllers on a BUS. The end of each bus should be terminated with a 120-ohm resistor or two 60-ohm resistors in series as shown in Figure 15. [23]

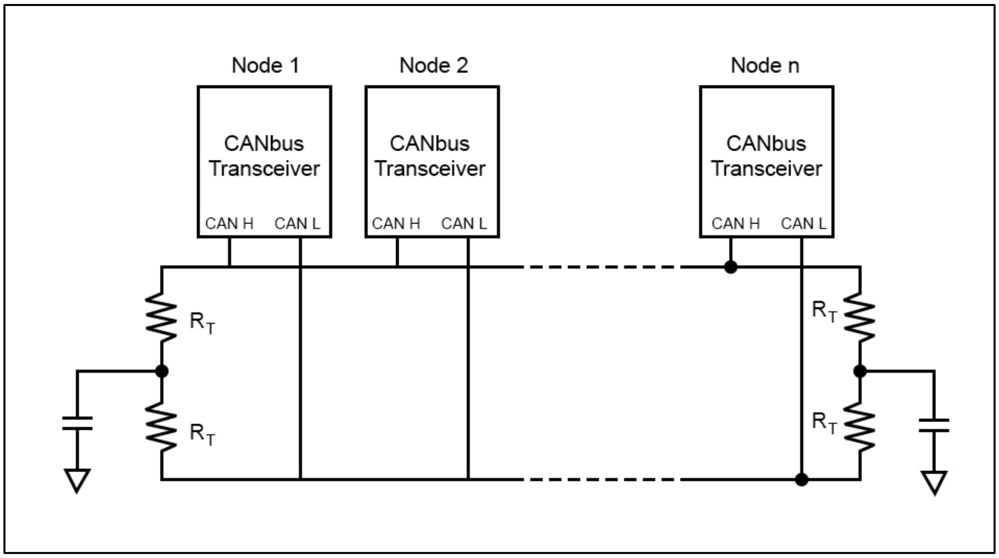

Figure 15: CAN Bus Generic Wiring Schematic

3.1.2 Digital and Analog Communication

Analog signals are often used to represent physical quantities. Temperature and pressure sensors utilize analog signals. A temperature sensor will output a voltage proportional to the temperature it measures. A control unit can read this analog signal to monitor the temperature. Analog signals are susceptible to noise, which can degrade the quality of the signal and makes it harder to interpret the data accurately.

Digital communication represents information using discrete values, in the form of binary (0s and 1s). Digital signals in the MAC Team vehicle are generally on/off or open-close signals. The MAC Team vehicle rear clutch controller uses four digital signals to control the rear clutch. A digital signal for an open clutch, a digital signal for closed, a digital signal to enable an open movement of the clutch, and a digital signal to enable a close movement of the clutch. Digital signals can be used to interoperate states and enable action. Combined with a tested state flow control, the result is a robust clutch control system. [24]

3.2 Component Testing

3.2.1 Rinehart Inverter/YASA P400 Bench Test

The purpose of the YASA P400 bench test was to establish consistent control of the motor functions, speed control, torque control, and gain software and hardware experience with the YASA motor. Experience with a component leads to integration success later in the development process. The YASA test bench setup comprises several components, including a dSPACE Microautobox, a YASA P400 motor, a Rinehart inverter motor controller, a high-voltage power supply, and a pre-charge circuit relay box. The dSPACE Microautobox serves as the MAC Team vehicle's main controller, communicating with all components via CAN, digital and analog communication. Figure 16 shows the YASA P400 test bench with all the components.

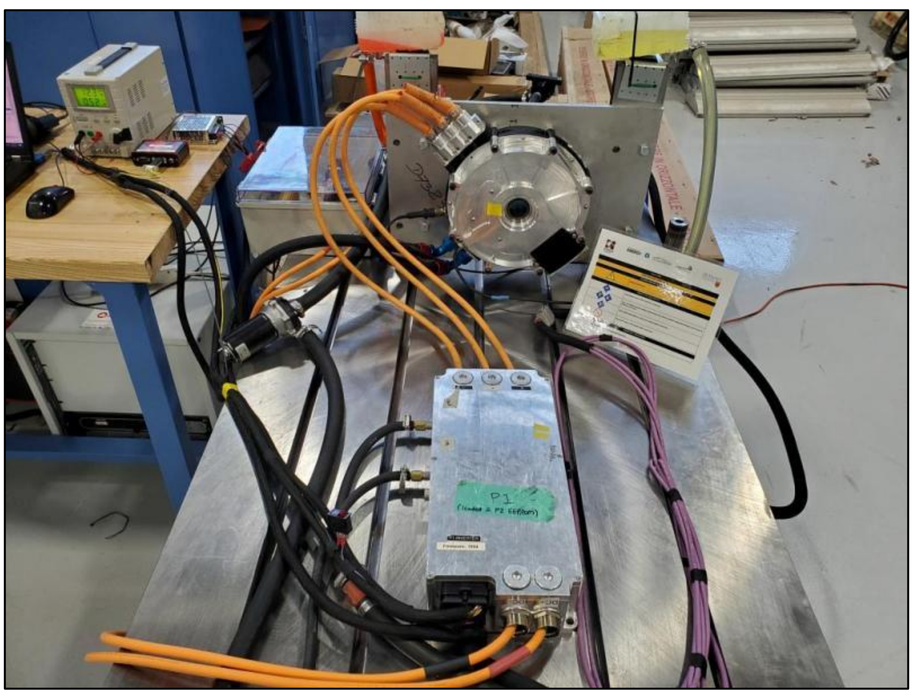

Figure 16: YASA P400/Rinehart Inverter Test Bench

This bench test familiarized users with the YASA P400 electric motor coupled with the Rinehart Motor Controller Inverter, gaining hardware and software knowledge. A cooling loop was created to cool the YASA and the Reinhart, a pre-charge circuit, HV wire harnesses, low voltage power and communication wire harnesses were created. The Reinhart requires EEPROMs (Electrically Erasable Programmable Read-Only Memory) to be set and calibrated for proper control of the YASA. This test bench also familiarized users with the MABx hardware and software, including proper pinning, generating Matlab Simulink code, flashing code onto the Mabx, and working with the Control Desk software. Control Desk enables users to monitor and interact with MABx code during operation, allowing users to adjust inputs and observe signals throughout the testing process.

To power the MABx, it is connected to a 12V power supply. For communication with Control Desk, it is connected to a laptop through an ethernet cable. The MABx communicates and controls the Rinehart inverter via a CAN bus, and the inverter, in turn, controls the YASA Motor via its 3-phase high voltage connection. Figure 16 shows the 3-phase connection between the Reinhart inverter and the YASA motor.

Canlyzer and control desk are used for analyzing data and manipulating signals during testing. Canylizer logs all CAN messages on the CAN bus. After a test, the CAN data can be reviewed within Canylizer. Control Desk gives users the ability to alter inputs in real time during a test. Internal signals not sent via the CAN bus can be observed in Control Desk via Simulink scopes, these scopes are useful for control loop development as they allow users to observe the current state a control loop is in. Observing the control loop state during a component test gives insight into the successes and failures of a given test.

The Matlab Simulink model developed for this bench test at a high level can be seen in Figure 17. This model is comprised of 3 sections. The dSPACE CAN transmit/receive block, the YASA/Reinhart control loop, and the YASA/Reinhart fault algorithm. The dSPACE CAN transmit/receive block corresponds to a specific hardware pin on the Mabx input/output (I/O). The MABx has 6 CAN I/O pins. Only one was needed for this bench test. Only two messages are transmitted to the CAN bus from this model, M192_Command_Message and M193_Read_Write_Param_Command.

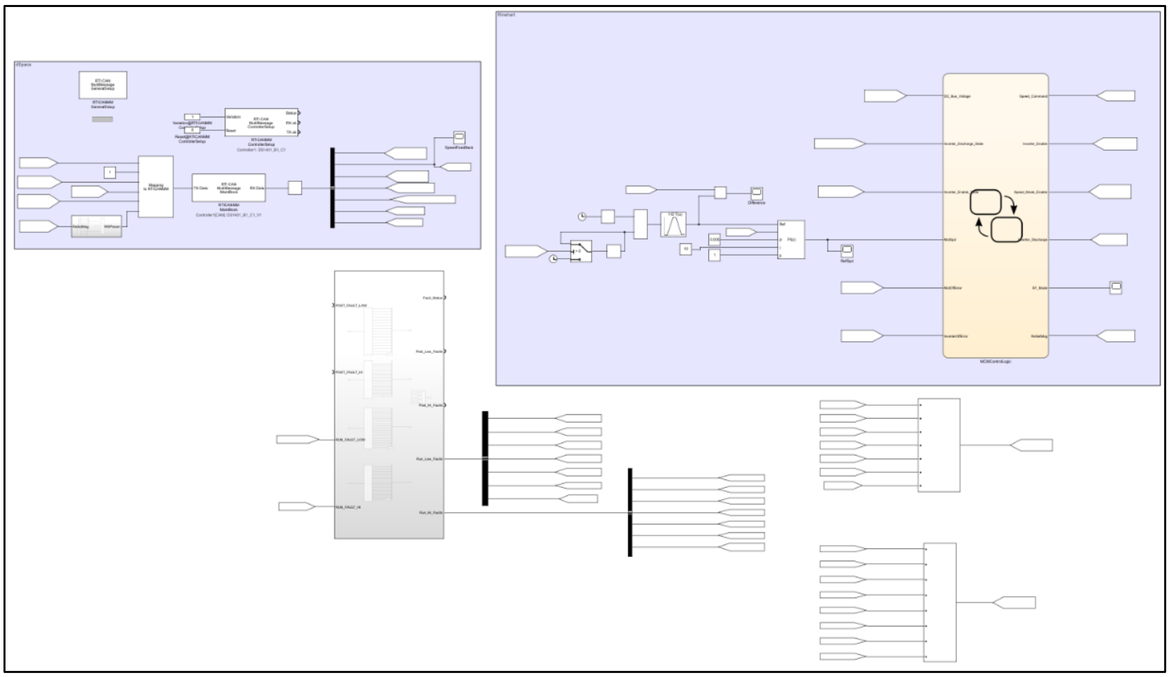

Figure 17: Rinehart Inverter/YASA P400 Top-level Bench Test Model

Within a message, there are specific signals that carry information used by the hardware. The M192_Command_Messsage contains the following signals:

- Speed_Command (RPM)
- Torque_Command (Nm)

- Direction_Command (0-1), which sets the positive rotational direction,
- Inverter_Enable (0-1)
- Inverter_Discharge (0-1)
- Speed_Mode_Enable (0-1), when speed mode is disabled (0), the YASA is in torque mode.

The M193_Read_Write_Param_Command is responsible for clearing fault states and contains three signals:

- Parameter_Address_Command (0-6250), a unique address identifies each command. Addresses are set and identified in the EEPROMs,
- Read_Write_Command (0-1), 0 is set for read, 1 is set for write,
- Data_Command (0-4095) writes data to the address set by the Parameter_Adress_Command.

This message is used to clear inverter faults. The sequence for clearing a fault is as follows:

Parameter_Address_Command: 20

Read_Write_Command: 1

Data_Command: 0

Once the fault was cleared, the message would go back to default.

The model receives six signals from the CAN bus transmitted by the Reinhart inverter that the model uses during testing. Figure 18 shows these six signals being output by the CAN receive block. These signals are:

- DC_Bus_Voltage (V)

- Motor_Speed (RPM)
- Inverter_Enable_State (0-1)
- Run_Fault_Low (0-32768)
- Run_Fault_High (0-32768)
- Inverter_Discharge_State (0-4)
    - 0 = Discharge Disable
    - 1 = Discharge Enable, Waiting,
    - 2 = Speed Check
    - 3 = Discharge Occurring
    - 4 = Discharge Complete

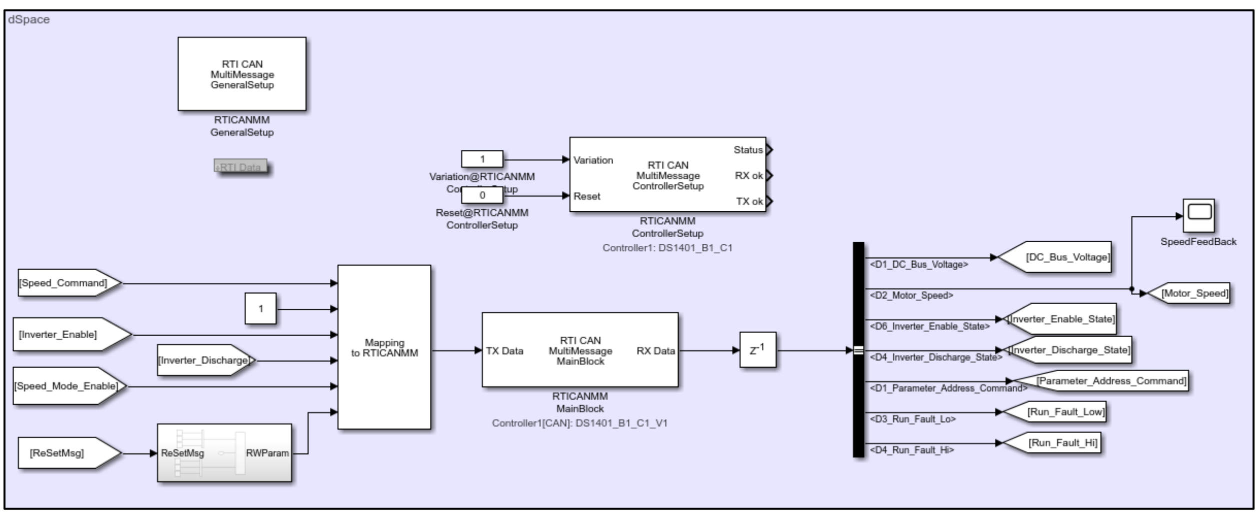

Figure 18: dSPACE CAN Bus Block Set Up for Rinehart/YASA Test Bench

Run_Fault_Low and Run_Fault_High are each responsible for 16 possible faults, each fault with a unique Byte value. If there are two or more faults active simultaneously, these byte values are added together. Due to this functionality, a script was developed to determine which faults were active during a fault state. The Rinehart EEPROMs set thresholds for many of these faults. For example, the Over-current fault has a byte value of 2, and the Motor Over-temp Fault has a byte value of 4096. If both faults were present, the Run_Fault_Low signal would equal 4098. This signal would be filtered through the fault algorithm and sent to the motor control loop to halt operation in a safe manner. During testing, if a fault was activated, the test was halted either by the motor control loop or by an emergency stop if necessary. Using Canlyzer to review CAN logs of the experiment to gain more information on the faults, a more robust knowledge of the fault system was developed. Tests were run to intentionally input a fault by lowering fault thresholds in the Reinhart EEPROMs to test how the motor control loop behaves when faced with a fault.

The motor control loop was developed using the Matlab Simulink Stateflow block. The Stateflow Block operates by defining a set of states, transitions, and actions for the system being modeled. Figure 19 shows the motor control loop has six defined states:

- PowerOff
- Startup1
- Startup2
- PowerOn
- Shutdown
- Fault state

The motor control loop Stateflow begins in the PowerOff state, moving to Startup1 when the start up condition is met. During this motor bench test, the start-up condition was when the HV power supply switched on and supplied over 275V. After a delay of 0.5 seconds, the state flow transitions to startup2. Startup2 sends the Rinehart inverter an enable request, upon confirmation that the inverter has enabled the Stateflow transition to the PowerOn state. The PowerOn State is responsible for torque requests and speed requests during testing. When the voltage from the power supply drops below 275V the Stateflow transitions to the Shutdown state, where an inverter discharge request is sent, and the inverter is disabled. The fault state can be transitioned from any state except for the PowerOff state. During testing, if a fault was detected, the motor control loop would enter a fault state. In a fault state, all motor commands are set to 0. After 2 seconds, the fault is cleared, and the motor control enters the Shutdown state. If a fault is detected, the test will stop, and the CAN data will be analyzed to determine the cause of the fault and prevention measures implemented into the new test control loop.

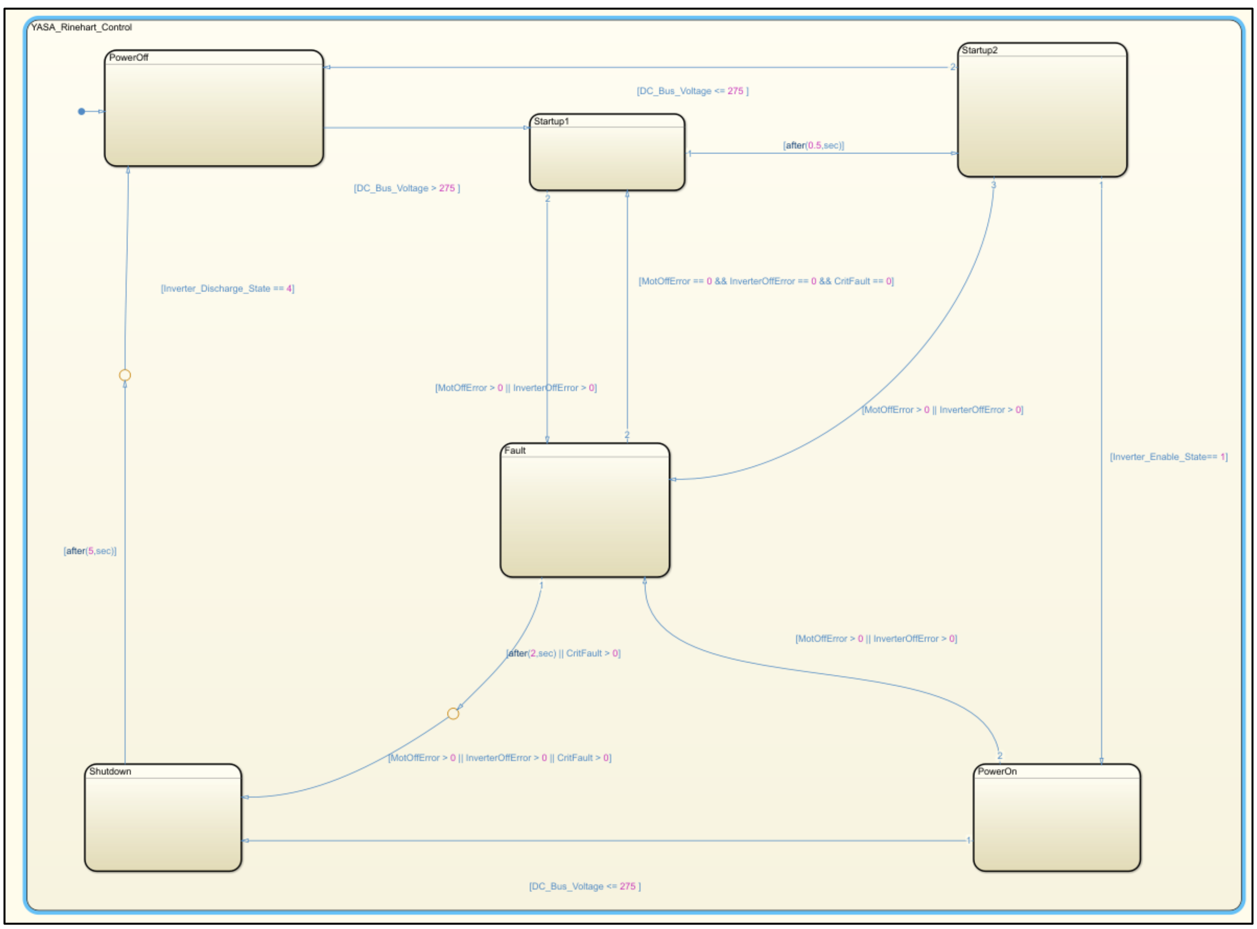

Figure 19: Motor Control Loop State Flow

A variety of tests were performed while this test bench was in operation. The majority were speed control tests. Figure 20 shows the software test apparatus for a speed mode test.

A signal builder block would initiate once the inverter was enabled and the motor control loop entered the PowerOn state. The signal builder would ramp the speed to 500 RPM and back down to 0 RPM. This test bench did not include a load on the YASA Motor which meant that torque mode testing was limited, but low torque tests were run, as well as mode transition, switching between torque mode and speed mode. Quickly switching between speed mode and torque mode was a feature used during clutch speed matching after vehicle integration.

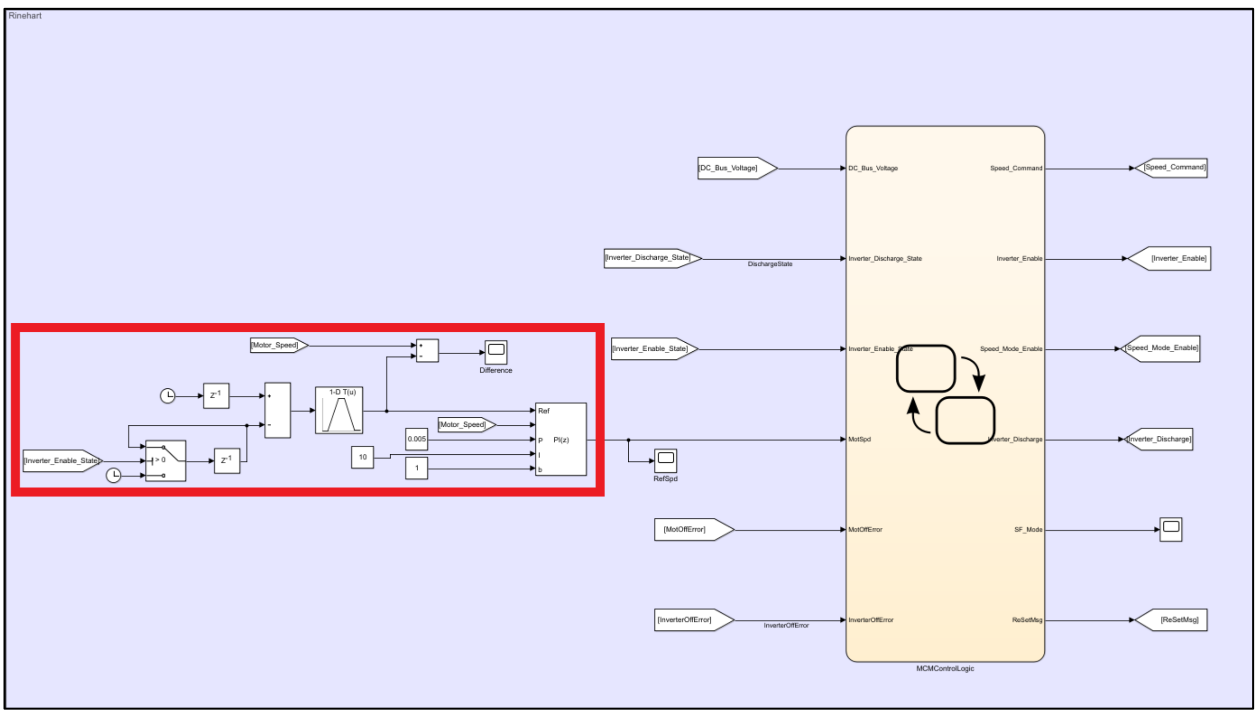

Figure 20: YASA Speed Test Software Apparatus

3.2.2 HEV4 Battery Pack Test Bench

The purpose of the HEV4 high voltage battery pack testing was to establish consistent control of the battery pack by opening and closing the pack contactors. The test setup includes a dSPACE Microautobox 2 (Mabx), the HEV4 Malibu high voltage battery pack, and two 12V power supplies. The battery testing process was conducted to establish effective control of the battery system through digital signals and CAN communication via the Mabx. The control model developed in Matlab Simulink for this testing comprised ten states within the state flow diagram. The battery control state flow was designed in accordance with General Motors' documentation. These states are:

- Off
- Start-Up
- Safety Check 1
- Safety Check 2
- Close Contactors Request
- Battery Pre-Charge
- Running
- Shutdown
- Bus Bleed Down
- Fault detection

Figure 21 shows the battery state flow developed for the battery pack testing.

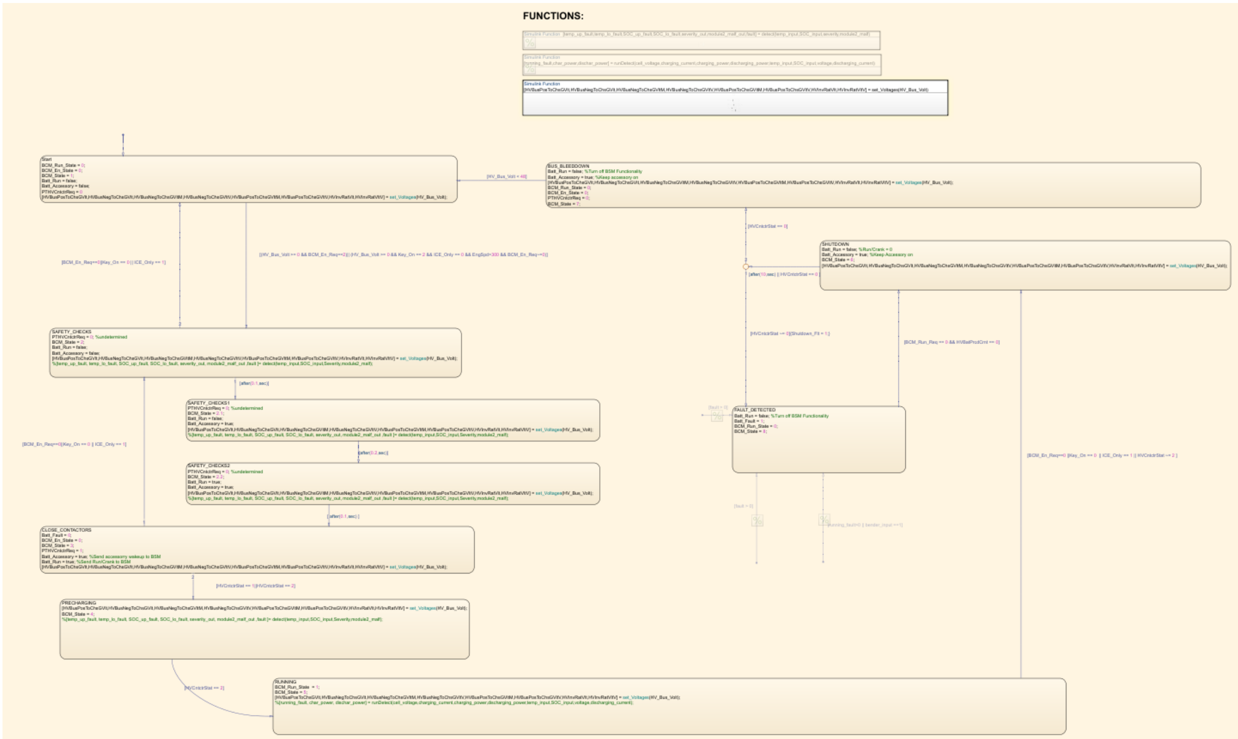

Figure 21: Battery Control Loop Stateflow

The testing procedure initiates when a MAC Team member activates the BCM_Enable switch in the Control Desk software. This action triggers the test, transitioning the system from the Start-Up state to safety check 1. In the safety check 1 state, a Wake Up digital signal is sent to the battery. This Wake Up signal enables CAN communication with the battery. After 0.2 second delay the system transitions to the safety check 2 state, during which a run/crank enable digital signal is send to the battery, this signal prepares the battery for a close contractor request via CAN. After 0.1 seconds, the ‘Close Contactors request’ state initiates, sending a “Contactors Close Request” message to the battery via CAN. Once the battery system processes this request, the battery undergoes a pre-charge sequence. Upon completion of the pre-charge sequence, the battery contactors close, and the battery control loop enters the ‘Running’ state. During testing, reaching the ‘running’ state was a successful test and after a few minutes in the ‘running’ state, the MAC Team member running the test would disable the BCM_Enable switch in Control Desk, which transitions the battery control loop to the 'Shutdown' State, this state sets the Run/Cranks digital signal to 0 which triggers open contactors sequence within the HEV4, once contractors have been opened the battery control loop transitions to the Bus Bleed Down state which keeps the battery accessory digital signal as true until the observed battery voltage drops below 48 volts and the test is ready to be run again.

These bench tests conducted with the YASA electric motor and HEV4 Battery Pack produced critical insight into their performance, functionality, and control structures. These comprehensive tests not only enhanced the team's understanding of these components but allowed the MAC Team to detect and rectify potential issues before vehicle integration, thus significantly reducing potential risks and delays in the development process.

3.2.3 Rear Driveline Test – YASA/HEV4 Vehicle Integration Test

The purpose of this test was to operate the YASA electric motor with the electrical power being supplied by the HEV4 battery pack, resulting in the rear wheels to rotate. This test was conducted on a lift, as seen in Figure 22. This test connected the motor control loop and the battery control loop developed during bench testing to operate together.

Figure 22: Rear of the MAC Team Vehicle on a Lift

This was also an electrical and mechanical integration test to evaluate the electrical connection between the HEV4 battery and the Rinehart inverter, and the mechanical connection between the YASA P400 and the wheels. The procedure for this test went as follows; initiate the battery control model with a signal sent from Control Desk by the team member conducting the test. The battery control loop sends the contactor close request, and the contactors close, enabling high voltage. Once the YASA is receiving high voltage and no faults are present, the team member would send torque requests through Control Desk to increase the torque output of the YASA by

1Nm until the rear wheels begin to spin and accelerate. Figure 23 shows the YASA motor CAN logs of the motor's commanded torque and the resultant motor speed, which also represents the rear wheels due to the mechanical attachment. The rear wheels begin to spin at 3Nm, and the YASA motor quickly reaches a maximum speed of roughly 400RPM. Each torque request would last between 20-30 seconds, and each time the YASA motor would reach a constant speed due to inertia and friction. Figure 24 shows the motor acceleration when the equilibrium is broken with an 8Nm torque request. This test confirmed the HV battery and YASA motor functionality within the MAC Team vehicle.

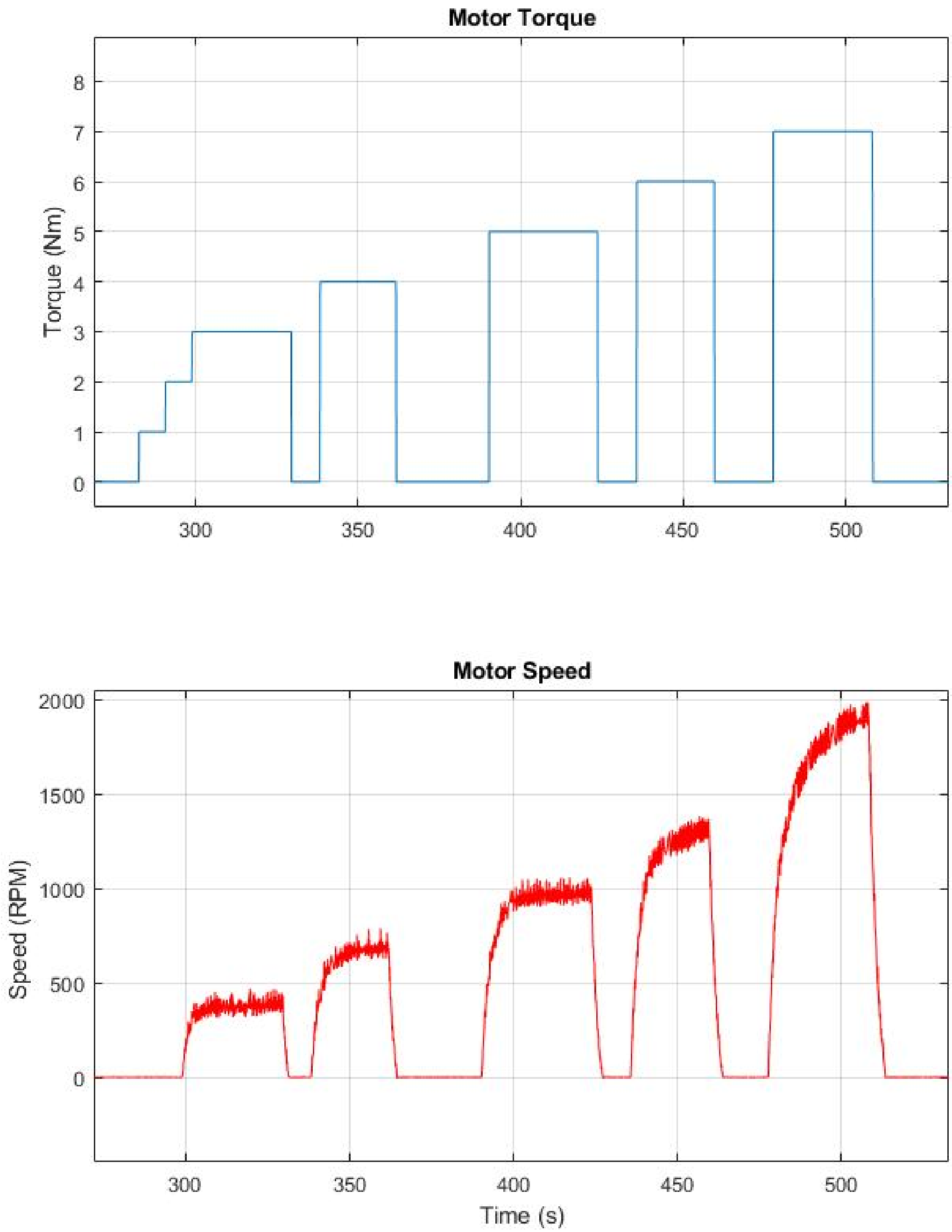

Figure 23: Motor Torque increasing 1-7Nm.

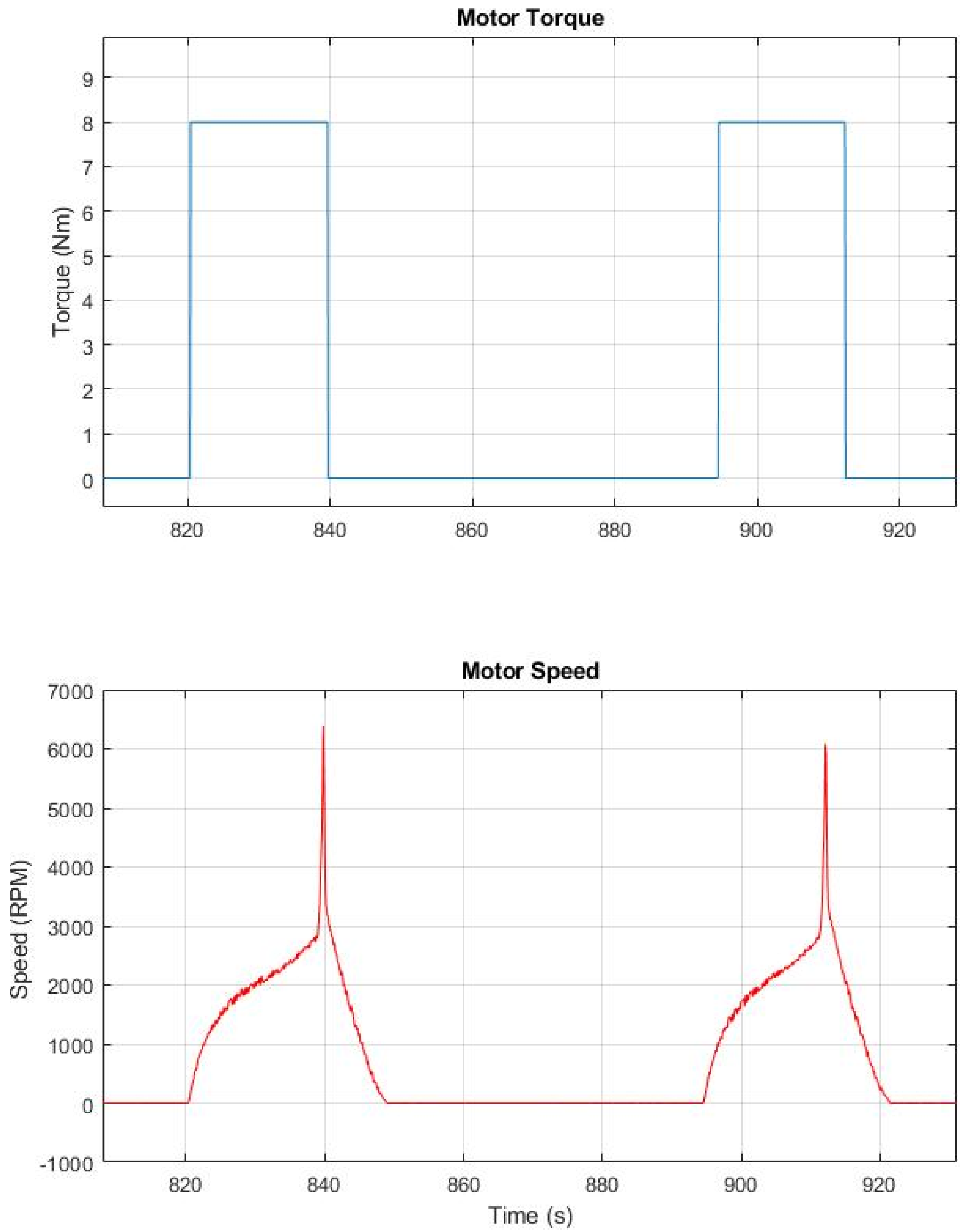

Figure 24: 8 Nm Motor Torque Request During Vehicle Lift Test

3.2.4 Belt Alternator Starter Test Bench

The purpose of the BAS test bench was to establish control of the BAS torque assist and regenerative capabilities. BAS bench test setup is comprised of a dSPACE Microautobox 2 (Mabx), two Valeo i-StARS BASs, a tensioner, and two 12V car batteries. The Valeo i-StARS BAS has torque assist and regenerative torque capabilities. The BAS torque assist function can be used to facilitate the start/stop operation of an engine, intended to be used in the MAC Team vehicle. Start/stop functionality is used to lower fuel consumption by turning off your engine when you stop at a red light, for example. The BAS torque assist can also assist the engine during regular driving operations. The BAS is responsible for maintaining the charge of the low-voltage system in the MAC Team vehicle. Figure 25 shows the BAS test setup. The BAS test setup had the two BASs connected to each other by a belt, each with their own connection to a 12V car battery and each with their own CAN bus connected to the Mabx. This test setup allowed the MAC Team to test both torque assisting and regenerative torque modes simultaneously, having one BAS producing torque and the other BAS resisting with regenerative torque. A MAC Team Member developed a BAS control loop for both BASs, one for torque assist and one for regenerative torque.

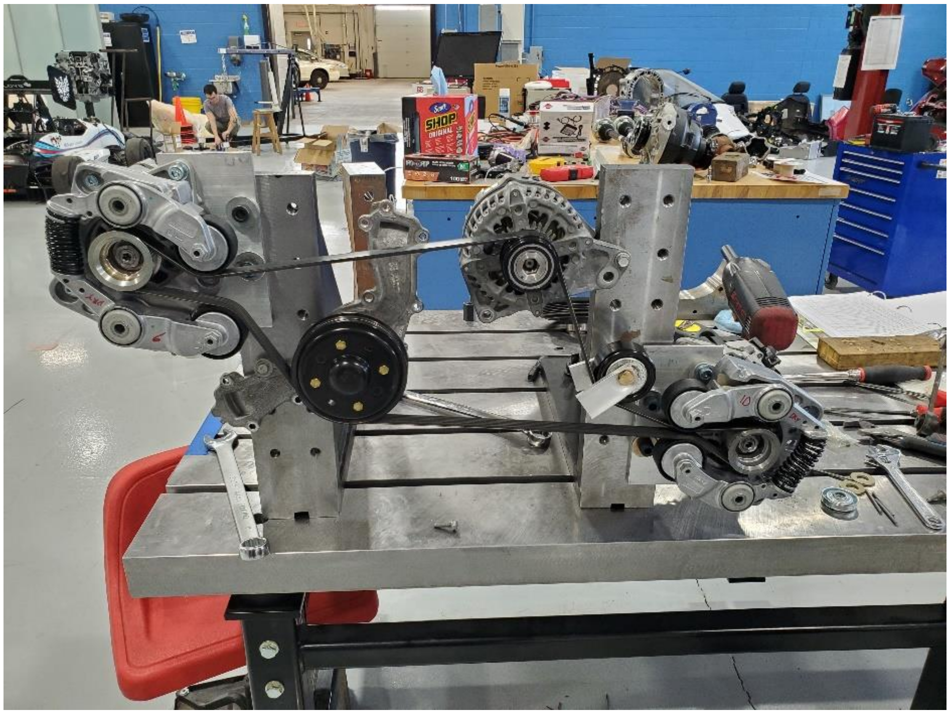

Figure 25: BAS Test Bench Setup

It was this BAS test where the MAC Team discovered a manufacturer error within both BASs used. The BASs had the incorrect flash code and were locked out of their ability to torque assist. The ability to apply regenerative torque was the only function the BAS was able to perform. This demonstrates the importance of testing prior to integration. Through communication with Valeo the MAC Team tried to rectify the error, but Valeo halted communication shortly after this discovery, so new firmware was not able to be flashed onto the i-StARS BAS. Testing continued but only regenerative torque mode was tested. These tests confirmed the MAC Teams' ability to control the BAS in a regenerative mode which was the minimum requirement needed from this component. A more vehicle-specific BAS control loop was developed once the BAS was integrated into the vehicle. Due to the firmware issue the BAS only operated in regenerative mode once integrated into the vehicle, charging the low voltage system.

3.4 Vehicle Testing

3.4.1 Serial Data Network Architecture

With the integration of the new GMC Terrain LYX Engine, YASA P400/Rinehart inverter, BAS, and HEV4 battery pack into the MAC Team vehicle, the stock 2019 Chevrolet Blazer serial data network architecture needed to be altered to accommodate these new components. Figure 26 shows the final serial data network architecture in the MAC Team Vehicle, which includes all stock and team added controllers. There are 5 CAN busses that connect the Mabx to the components in the vehicle, HS GM LAN, HS ECM LAN, HS ECO LAN, HS Battery LAN, and HS CAVs_PCM LAN. Each of these CAN busses operates at 500 kb/s.

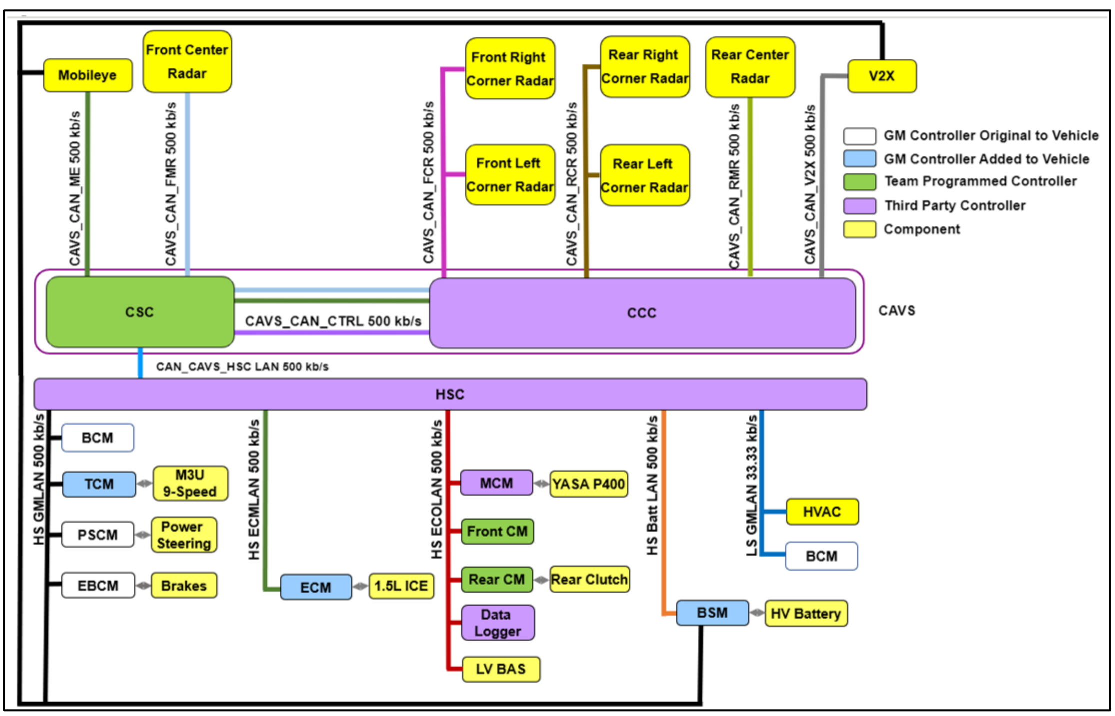

Figure 26: MAC Team Vehicle Serial Data Network Architecture

3.4.2 HS GM LAN & HS ECM LAN

The HS GM LAN is the main communication line of the stock vehicle, with connections to the Body Control Module (BCM), Transmission Control Module (TCM), Power Steering Control Module (PSCM), the Electronic Brake Control Module (EBCM) and the dSPACE Microautobox. The Engine Control Module (ECM) is connected to the HS GM LAN in the stock vehicle, but in the MAC Team vehicle, the ECM was removed from HS GM LAN and a new CAN bus was created for the HS ECM LAN. This CAN bus only connects the Mabx and the ECM. The ECM requires HS GM LAN messages and signals to operate properly. These messages and signals are gatewayed by the Mabx from HS GM LAN to HS ECM LAN. This allowed the MAC Team to alter messages and signals from HS GM LAN to gain full control of the ECM and engine in the MAC vehicle.

3.4.3 HS ECOLAN

HS ECOLAN is the main CAN bus for all MAC Team added components, with connections to the Rinehart inverter motor controller, the BAS and the front indicator board. The front indicator board was a PCB designed by the MAC Team and was used to convey information to the driver of the vehicle and for the driver to set driving conditions.

3.4.4 HS Battery LAN

The HS Battery LAN is the CAN bus that connects the HEV4 battery pack to the MABx. The HEV4 battery pack is also connected to the HS GM LAN, but this connection is for internal HEV4 use. The MAC Team did not manipulate this connection.

3.4.5 HS CAVs_PCM LAN

The HS CAVs_PCM LAN is used by the MAC CAVs Team to communicate and interface with the HSC. This connection was used exclusively during MAC CAVs Team testing and not during on-road vehicle operation.

3.4.6 Vehicle Dynamometer Testing

A vehicle dynamometer, also known as a chassis dynamometer, can be used to measure the power output of a vehicle. The vehicle is attached to the dynamometer by all four wheels and held stationary. Each wheel is attached to a brake dynamometer. These brake dynamometers apply a load to the wheels to simulate different driving conditions. Figure 27 is a picture of the MAC Team vehicle attached to the chassis dyno. The dyno allowed the MAC Team to perform tests at varying speeds for multiple minutes at a time, a luxury never found in a research parking lots. The MAC Team vehicle operated at all speeds while attached to the dyno, giving the MAC Team more insight into the operation of our vehicle. The purpose of the chassis dyno testing was to perform engine torque control testing and to develop a clutch speed-matching algorithm for opening and closing the clutch at speed. The engine torque control testing requires the vehicle to be crawling for extended periods. The clutch speed matching algorithm was testing the speed matching at a constant 40km/h. For a single test, the vehicle might travel over 1.5km.

Figure 27: MAC Team Vehicle on Chassis Dynamometer

3.4.7 Engine Torque Control Testing

The goal of this test was to establish torque control of the MAC Team engine. The stock engine outputs torque based on the driver pedal position, but when the engine is in adaptive cruise control (ACC) mode, the ECM receives torque requests from the EBCM and the adaptive cruise control algorithms. The stock vehicle enters adaptive cruise control when the driver presses a sequence of buttons on the steering wheel that are sent through CAN to the ECM. If the button has been pressed in the proper sequence, the engine enters ACC mode. The Simulink engine control module within the MABx attempts to enter the stock Blazer ACC mode by mimicking the steering wheel button pressing sequence. To successfully enter ACC mode, three signals must be sent to the engine, Cruise On, Set, ACC Activate. Figure 28 shows the MAC Team developed Stateflow that sends Cruise On, Set, ACC Activate in the proper sequence. The simplest sequence is as follows; When the vehicle is in gear and begins to crawl, the Cruise On signal is sent for 0.2 seconds. This mimics an initial steering wheel button press. A feedback signal from the vehicle confirms that cruise control is enabled but not active yet. After 1 second of cruise control being enabled, the Set signal is sent for 0.2 seconds, and after another 0.1 seconds, the ACC Activate signal is sent. The ACC Activate signal continuously sends while the engine operates in ACC mode. Figure 29 shows the sequence in CAN, followed by the vehicle accelerating from a crawl of 9km/h to 20 km/h based on new engine torque values.

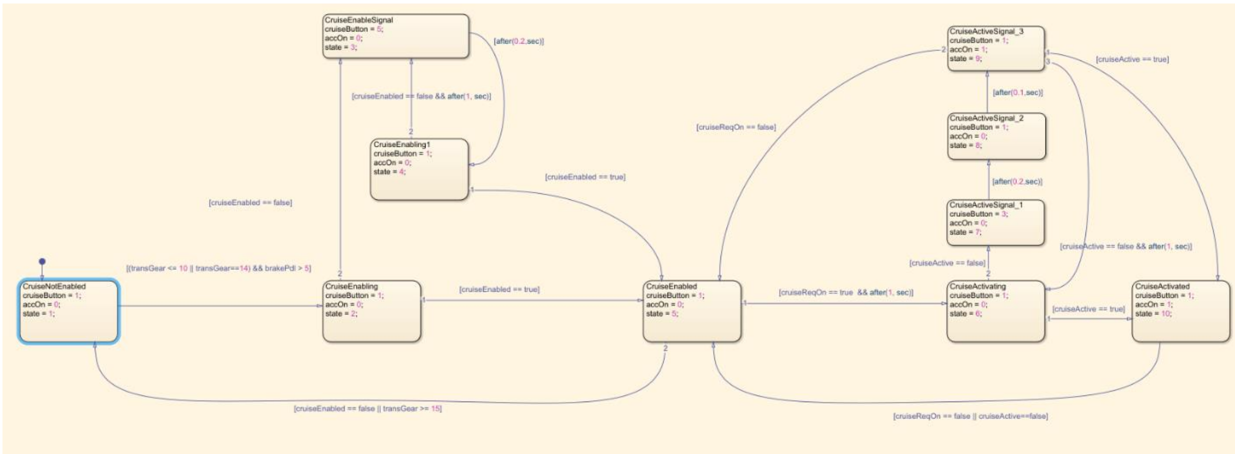

Figure 28: Button Pressing Stateflow - Software Engine Control Module

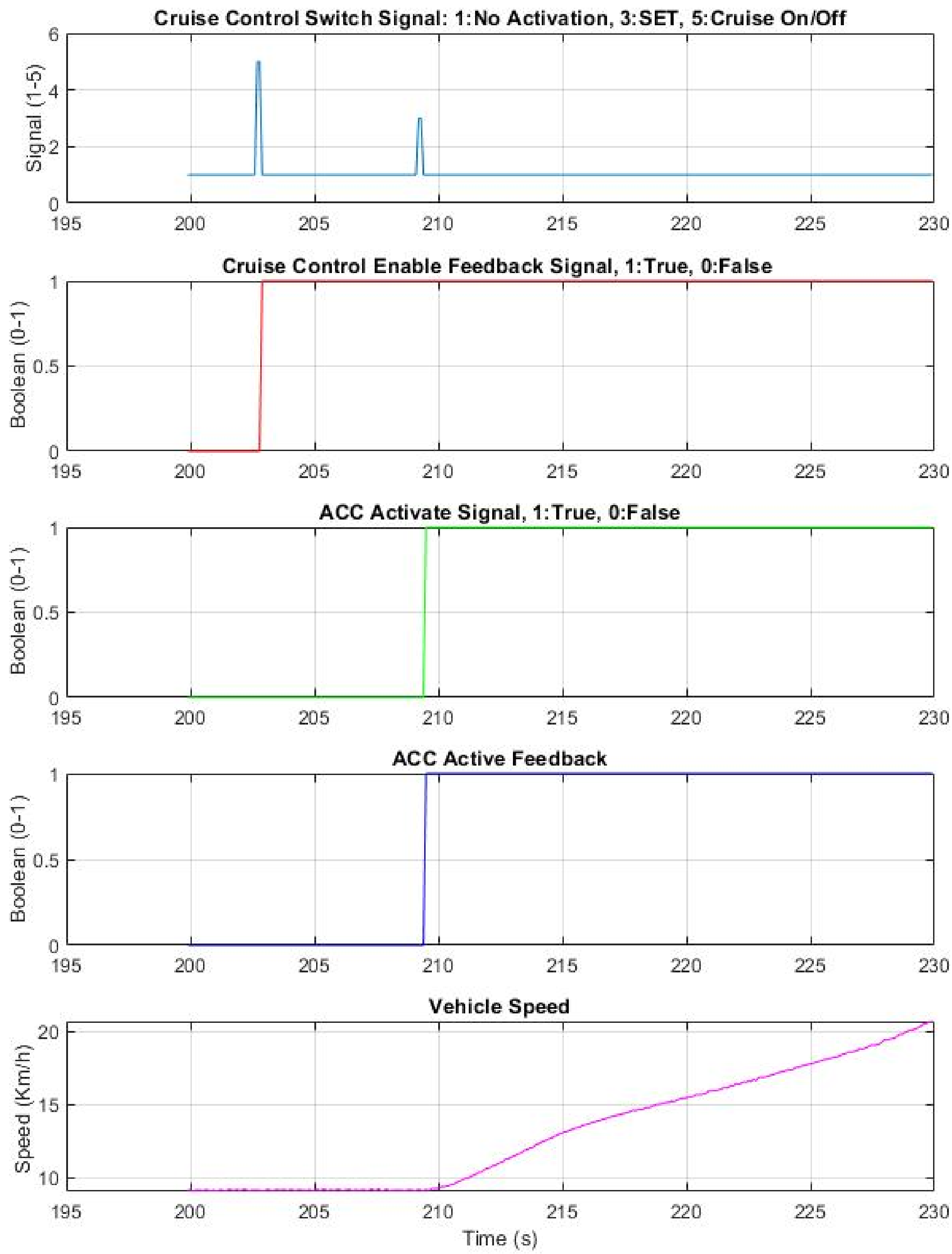

Figure 29: ACC Activated during Vehicle Dyno Testing

3.4.8 Clutch Speed-Matching Tests

The goal of the clutch speed matching test was to confirm the functionality of the algorithm that matches the motor's speed to the current vehicle speed for seamless closing of the clutch at high speeds. Figure 30 shows the YASA motor matching and maintaining the speed of the vehicle.

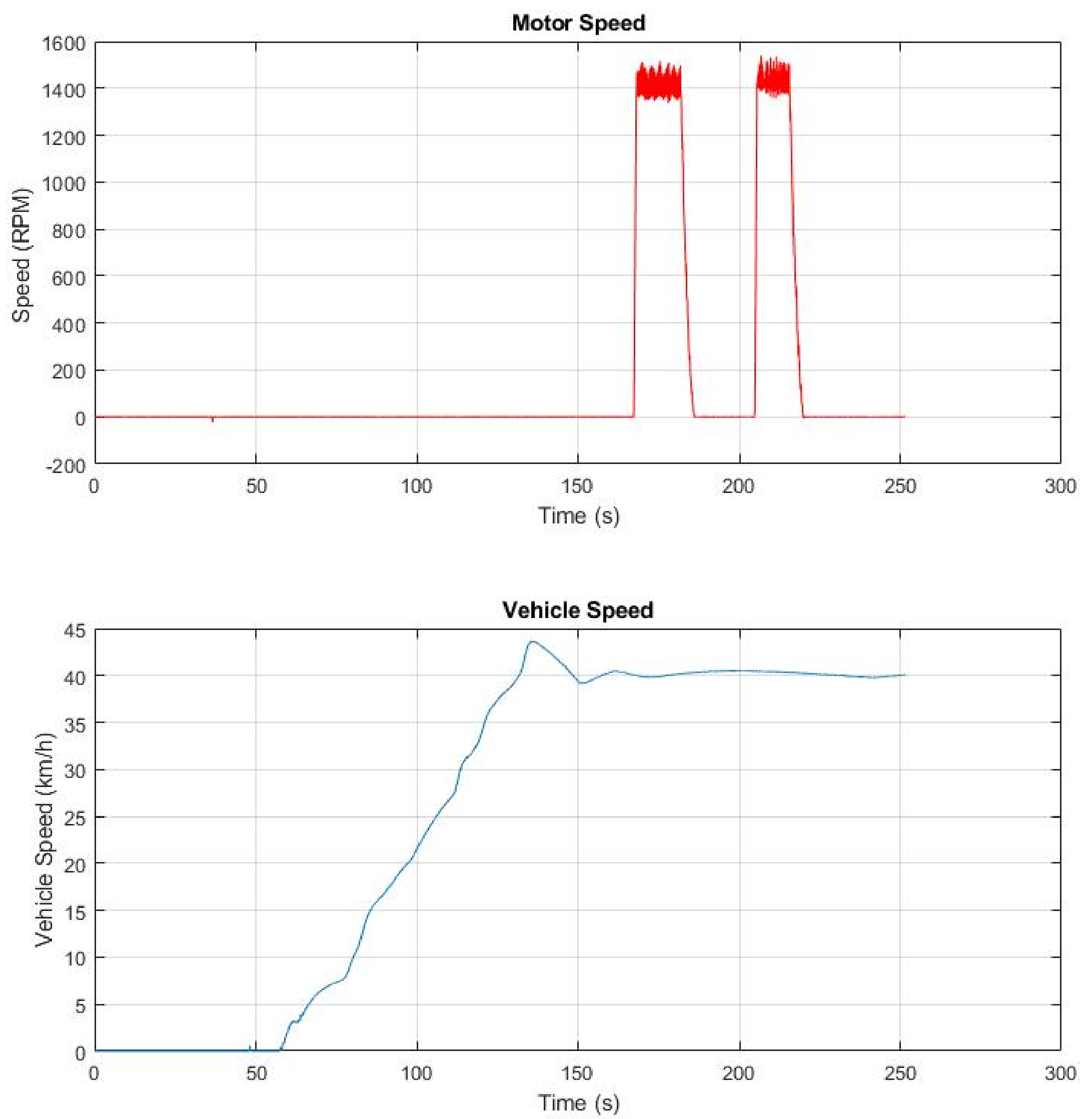

Figure 30: YASA Motor speed matching at 40km/h

3.5 Summary

This chapter focuses on the testing and control system implementation of the MAC Team vehicle’s components, including the Valeo i-StARS BAS, the Malibu HEV4 High Voltage battery pack, and the YASA P400 electric motor. The dSPACE Microautobox 2 was used as the main controller for all testing because it will be used as the main controller in the MAC Team vehicle. Component tests were crucial in understanding the performance, functionality and control structures of these components, and in detecting and rectifying potential issues before vehicle integration. Initial vehicle testing was also discussed in this chapter, chassis dynamometer testing, engine torque control testing via stock Blazer ACC and clutch speed matching were important tests to confirm vehicle component cohesiveness.

Chapter 4

Vehicle Control System

The vehicle control System is responsible for engine control, battery control, BAS control, motor control, rear clutch control, and regenerative braking control. This vehicle control system manages and coordinates with the various modules to ensure optimal performance by maximizing fuel efficiency, maintaining charge-sustaining of the high-voltage battery, and maintain comfortable driveability for the driver.

The full vehicle control system consists of 10 modules, Figure 32 shows the top-level control system, colour coded by the contribution of the Author, Green represents full contribution, yellow represents a team of 2 including the author and red represents no contribution from the author. All sections not highlighted are supplementary blocks for the modules or communication blocks that interface with hardware, all of which was developed by the author. The 10 control modules are as follows:

- Energy Management Module (EMM) (Green)
- Engine Control Module (ECM) (Yellow)
- Battery Control Module (BCM) (Yellow)
- BAS Control Module (BASCM) (Yellow)
- Motor Control Module (MCM) (Green)
- Gateway Interface Module (GIM) (Green)

- Clutch Control Module (CCM) (Green)
- CAVs Control Module (CAVCM) (Red)
- Regenerative Braking Control Module (RBCM) (Green)
- Indicator Board Control Module (IBCM) (Green)

Each of these modules was developed through Model-in-the-loop, Hardware-in-the-loop, and Vehicle-in-the-loop. MIL development utilized the Matlab Simulink model described in Chapter 2. HIL development consisted of bench-testing hardware to develop control loops, modules, and communication. VIL development tested and finalized each module within the vehicle control system. VIL testing encapsulates a wide range of tests, from component integration tests, and chassis dyno tests, to on-road vehicle testing. The MAC Team established a McMaster dive cycle for on-road vehicle tests. The MAC Team was required to conduct all on-road tests following the McMaster drive cycle. This mandate provides a consistent baseline and ensures that the results from different vehicle control system tests are comparable. Figure 31 shows the McMaster drive cycle overlayed on the map of Hamilton, Ontario. The MAC Team vehicle control system was developed over thousands of model simulations, hundreds of hours of troubleshooting and testing, three component bench tests, over 50 hours of closed track time, two months of chassis dyno time, and over 1500km of on-road driving. Figure 32 shows the top-level Simulink model of the MAC Team vehicle control system, this model is generated into code and flashed onto the MABx in order to interface with the MAC Team vehicle. Each module's input and output can be observed from the top level.

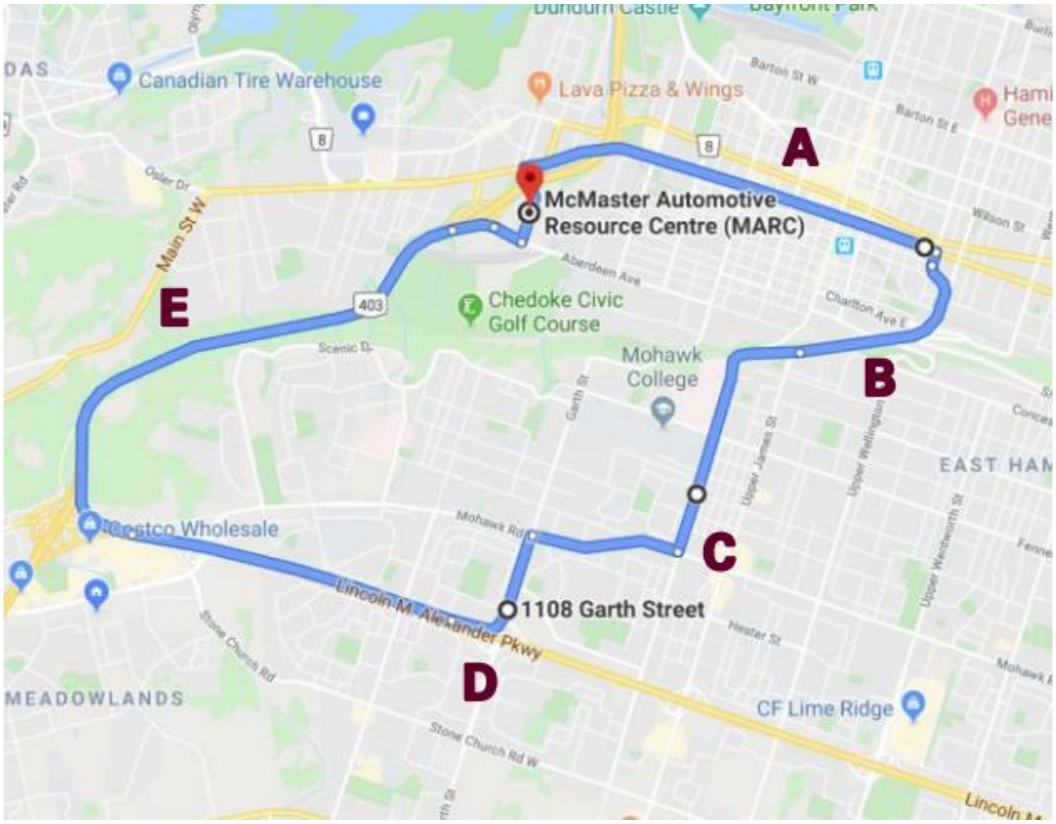

Figure 31: GPS McMaster Drive Cycle Route through Hamilton

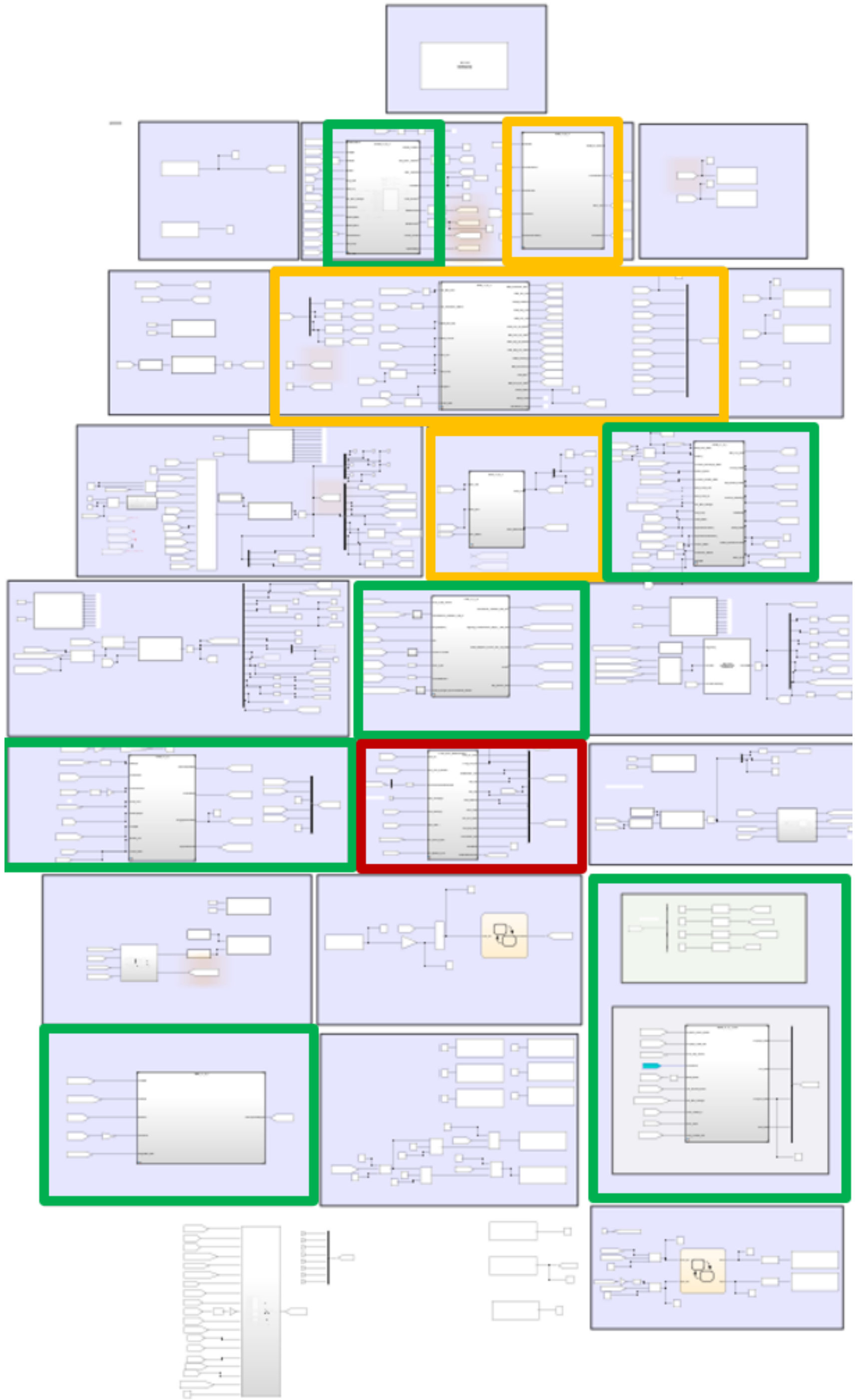

Figure 32: Top Level Hybrid Supervisory Control

4.1 Energy Management Module

The EMM was developed through MIL simulation and on-road vehicle testing. The energy management module is responsible for the torque split strategy between the YASA electric motor and the ICE. Also responsible for charge sustaining of the high voltage battery. This module was tested and developed in MIL and refined in VIL. The inputs for this module are:

- Accelerator pedal position [0-100]
- Vehicle speed [km/h]
- Motor speed [RPM]
- Transmission gear [0-14]
- Wheel speed [RPM]
- ICE speed [RPM}
- State of charge of the high voltage battery [%]
- ICE only switch signal [0-1]
- Voltage of the HV battery [V]
- Charge-sustaining constants, Range and Curvature.

The most impactful inputs are the accelerator pedal position and the vehicle speed. These two inputs are used to determine the wheel torque command of the driver. The wheel torque command is determined using a 2D lookup table. The two inputs of this 2D lookup table (LUT) are accelerator pedal position and vehicle speed. The output of this 2D LUT is the wheel torque command. This 2D look-up table is also known as the pedal map. General Motors supplied this pedal map, and is the standard pedal map used in stock GM vehicles. Figure 33 shows the EMM inputs and the 2D lookup table inputs.

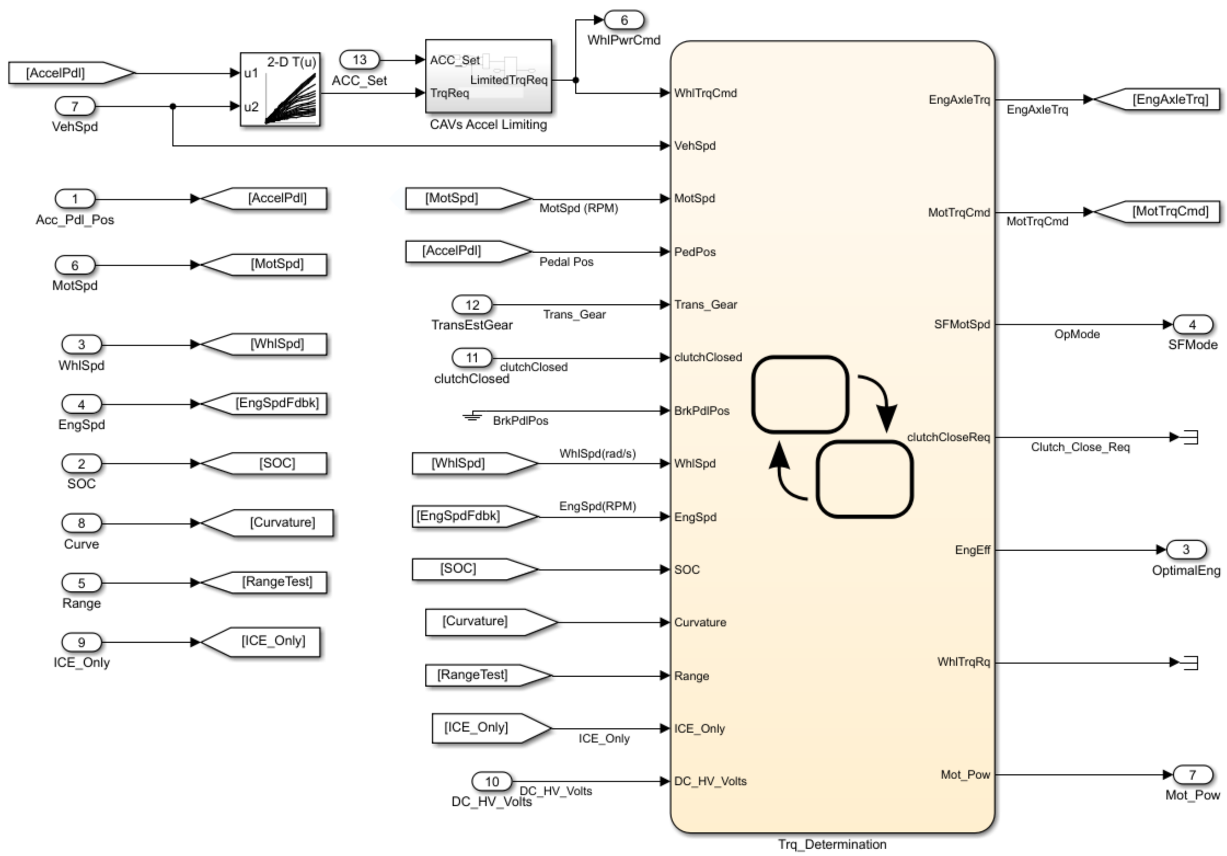

Figure 33: EMM Top-level State Flow

The EMM utilizes a Stateflow block with four unique states, vehicle crawl, torque split state, high acceleration, and ICE only. The crawl state is an engine-only operation and replicates the low-speed operation of other automatic vehicles, this is a stock vehicle operation that is unable to be altered. When the driver releases the brake pedal, the vehicle will crawl forward. Once the vehicle reaches 6km/h, the EMM Stateflow transitions to the torque split state. Figure 34 shows the four states of the EMM and the transition conditions.

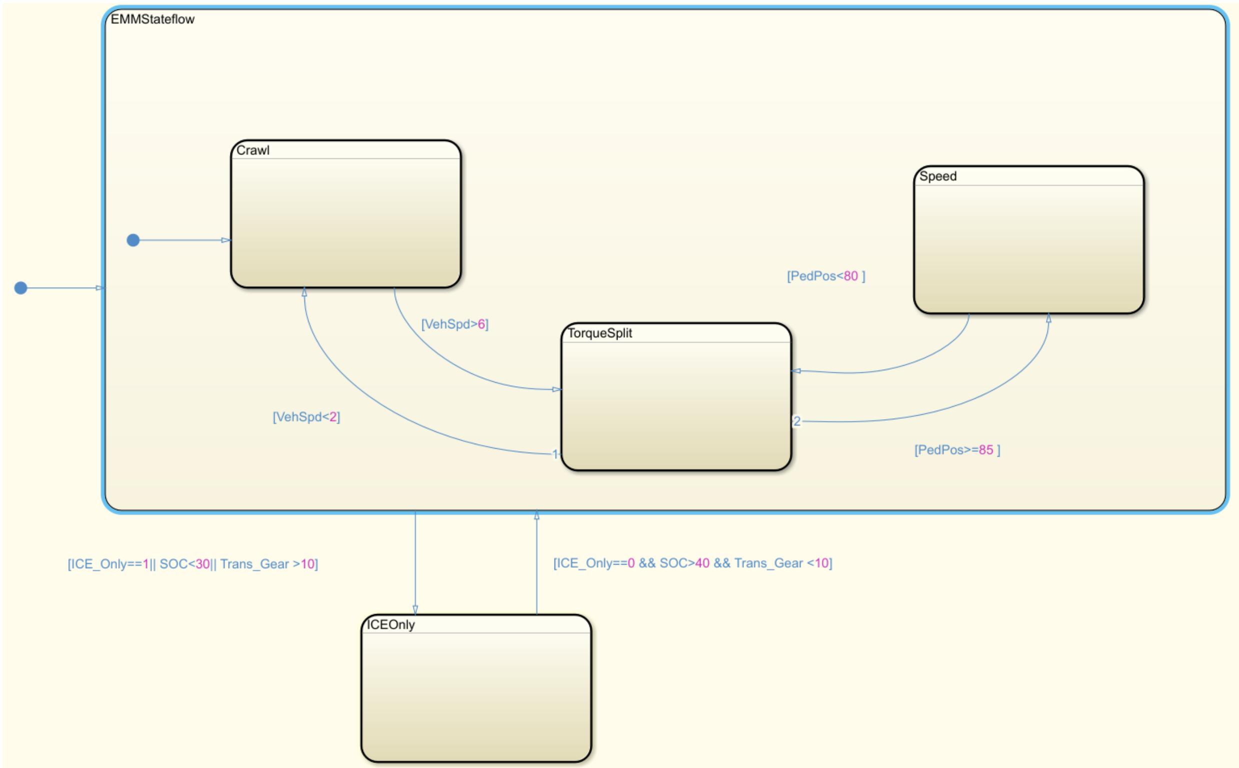

Figure 34: Energy Management Module four Stateflow states, Crawl, TorqueSplit, Speed and ICEOnly

4.1.1 Torque Split

A torque split control strategy must fulfill the wheel torque request of the driver. The components tasked with fulfilling this wheel torque command are the ICE and EM. The goal of this torque split control strategy is to operate the engine along its most efficient points throughout a drive cycle, using the EM to support the ICE. The most fuel-efficient operation of the ICE occurs along the Optimal Efficiency Line (OEL), seen in Figure 35. This line is defined by operating the engine at its most efficient torque output for the engine's current rotational speed, producing the lowest fuel consumption of the engine. Figure 35 shows the general shape of the MAC Team engine's optimal efficiency torque as rotational speed increases.

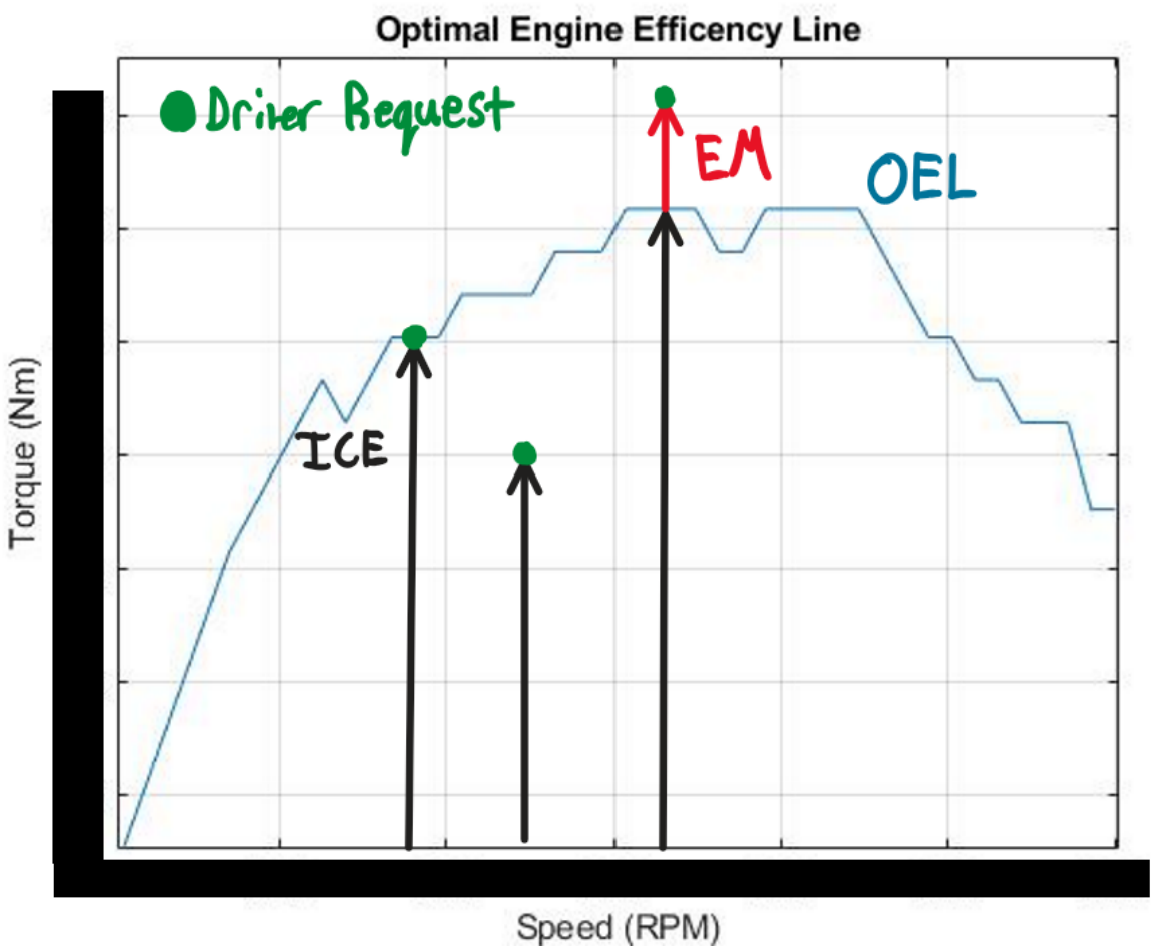

Figure 35: MAC Team Engine Optimal Efficiency Line

Requesting torque from the optimal efficiency line can improve efficiency but does not consider the drivers' wheel torque request. This OEL is very specific, and the likelihood that the driver torque request falls exactly on the OEL is low. The electric motor torque request is calculated by the torque difference between the optimal engine torque and the driver torque request, but only if the torque request falls above the OEL, this is represented in Figure 35 and Equation 3. When the torque request is below the OEL, driveability issues may occur. Figure 36 shows the result of this issue when tested in MIL. The OEL outputs a torque larger than the drivers request causing the driver to alternate between acceleration and braking to keep the vehicle at a constant speed. Driveability is an important condition to consider when developing a vehicle's energy management strategy, not only for the driver's sake but also for the fuel efficiency of the vehicle. Figure 36 shows sections during a drive cycle that will reduce the vehicles overall fuel efficiency.

Equation 3: Electric Motor Torque Request Calculation

$$T_{EM} = \begin{cases} T_{Drive\_Request} - T_{ICE\_OEL}, & T_{Drive\_Request} > T_{ICE\_OEL} \\ 0, & T_{Drive\_Request} < T_{ICE\_OEL} \end{cases}$$

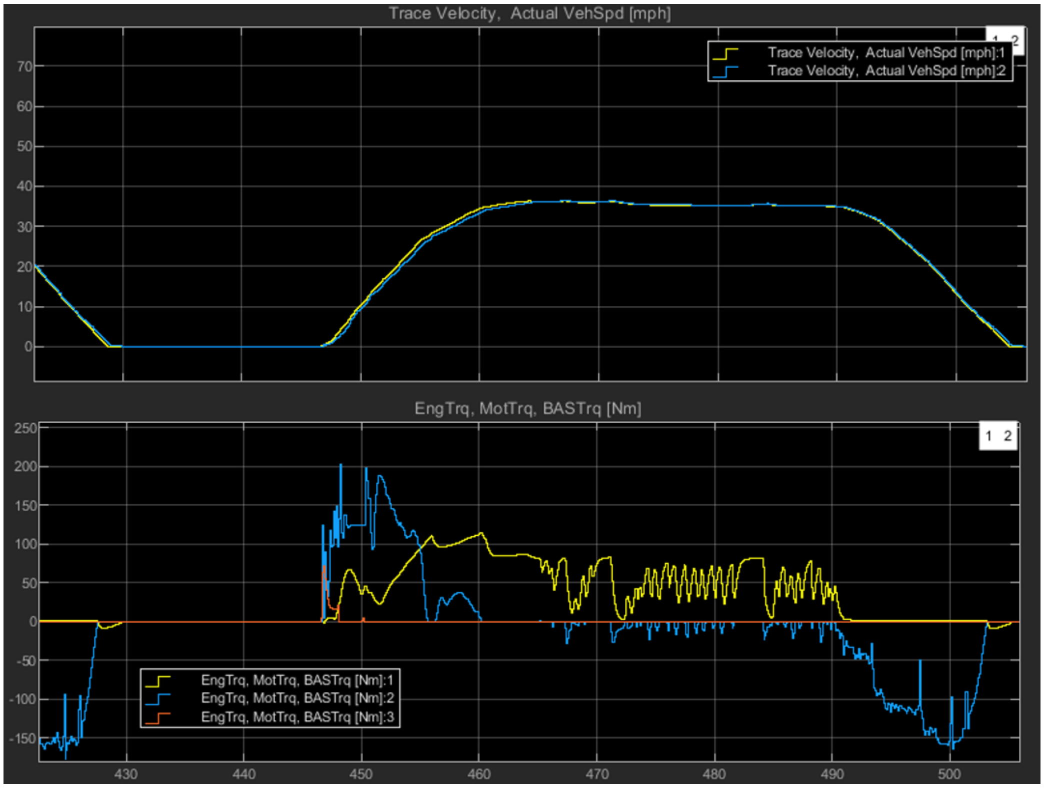

Figure 36: Poor Driveability During Drive Cycle Due to OEL Torque Output

Figure 36 & 38 displays the visualization block the MAC Team Members interface with throughout the MIL process. In Figures 36 & 38 the top graph displays the drive cycle target velocity of the vehicle and the simulated velocity of the vehicle. Yellow corresponds to the Drive Cycle target velocity or Trace Velocity, and blue corresponds to the simulated vehicle velocity. The velocity units are miles per hour. The bottom graph displays the torque output from the ICE and the YASA motor. The ICE torque is in yellow, and the YASA motor torque is in blue, the torque units are Newton-meters. The drive cycle section seen in both Figures 36 & 38 is from the EcoCAR Mobility Challenge city drive cycle. Figure 37 shows the EMC city drive cycle, and the red rectangle is the drive cycle section displayed in Figures 36 & 38.

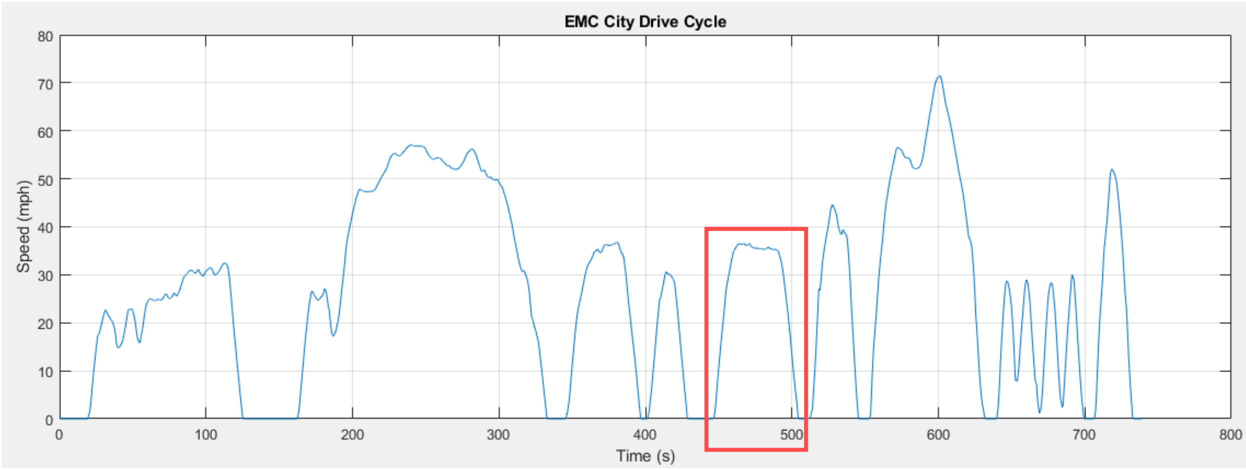

Figure 37: ECM City drive cycle

The EM torque output is designed to support the ICE when the driver's torque request is above the OEL. When the torque request falls below OEL, the engine is the only component able to fulfill the driver's torque request. This solves the driveability problem found in Figure 36. Leads to improved driveability and higher overall fuel efficiency, even though the engine operates on the OEL less over a drive cycle. Figure 38 showcases the improvement in driveability.

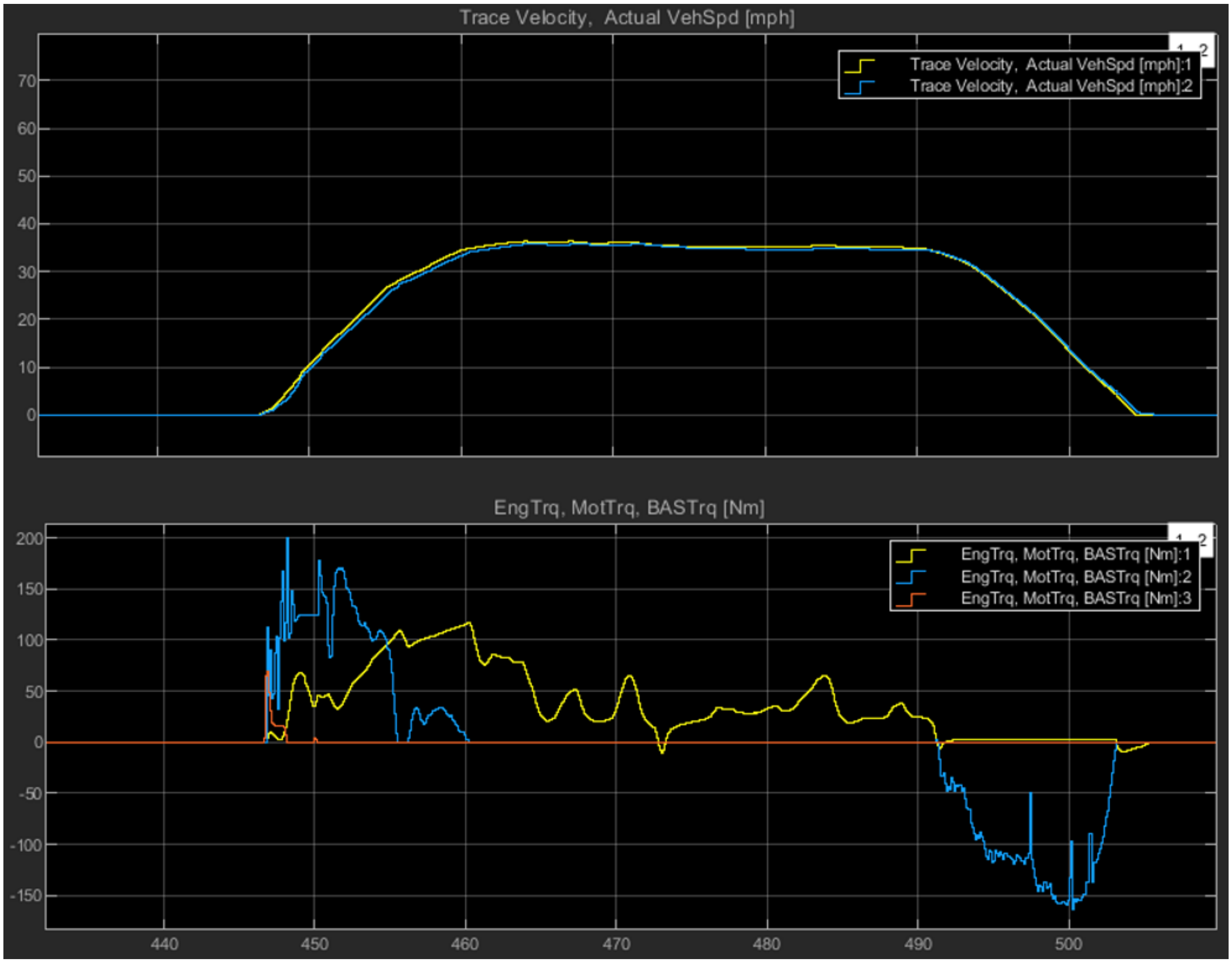

Figure 38: Improved Driveability During EMC City Drive Cycle

The EM supports the ICE while accelerating to increase fuel efficiency. This is illustrated in the 440 to 460-second range in Figure 38. The EM supports the ICE when the driver's torque request is larger than the OEL. When the request is above OEL, the engine operates along the OEL, and the EM closes the gap to the request. If the torque request is too large for the EM to reach while the engine operates on the OEL, the engine will increase its torque output to fulfill the driver's request.

Vehicle CAN logs from on-road testing show the YASA supporting the ICE during acceleration events. During two separate McMaster Drive cycle tests, one test was run in ICE-only mode and one test was run in hybrid mode. During each drive cycle an acceleration event from 20-60km/h. Figures 39 & 40 capture this acceleration event. Figure 39 displays the hybrid acceleration event showing the motor and ICE torque outputs and Figure 40 shows the ICE only acceleration event. During hybrid acceleration, the electric motor outputs the larger torque burden with the engine torque reaching a peak of 200Nm. The ICE-only acceleration sees a peak of 250Nm from the engine.

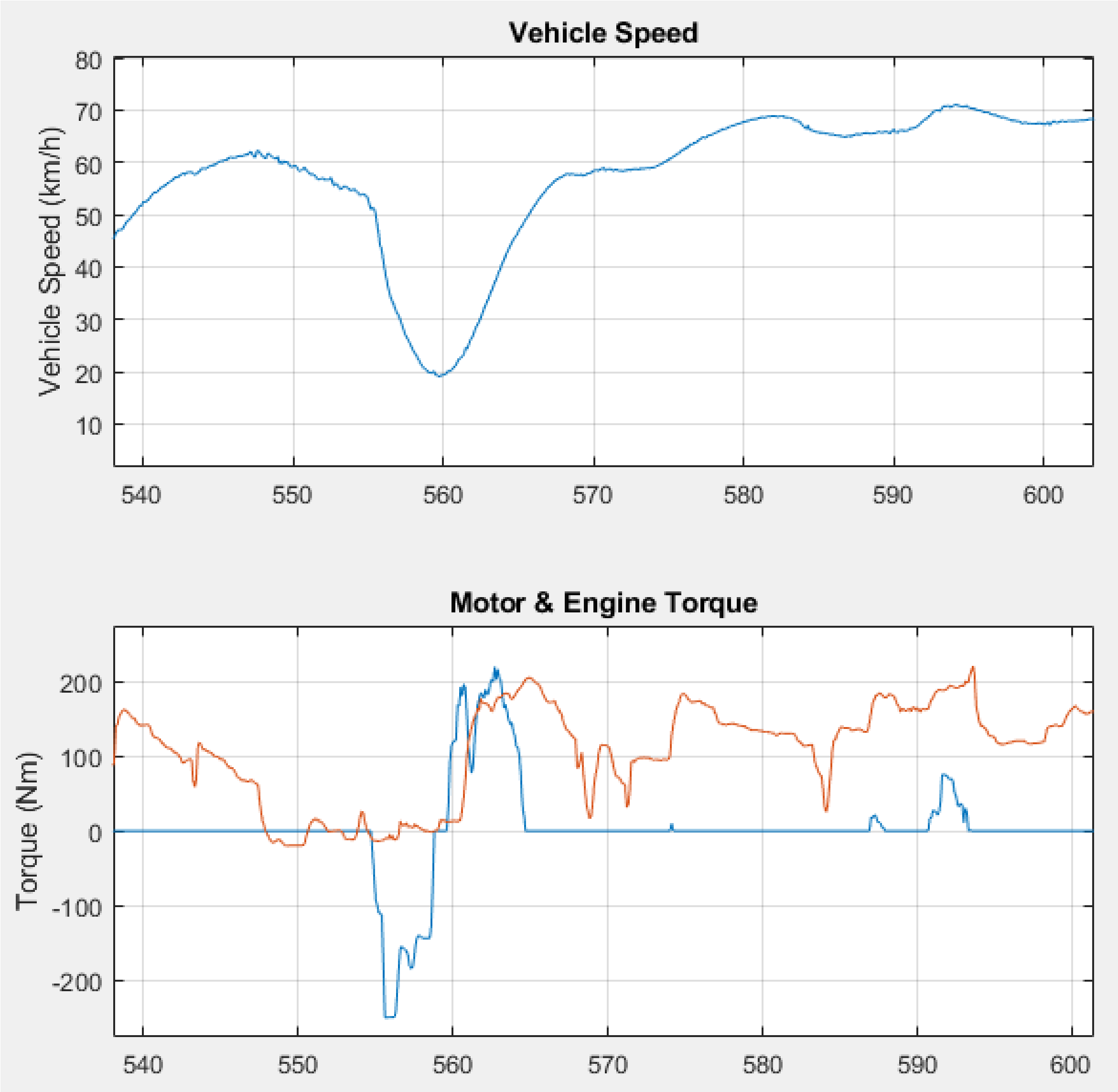

Figure 39: Motor Torque Assist During Acceleration 20-60km/h

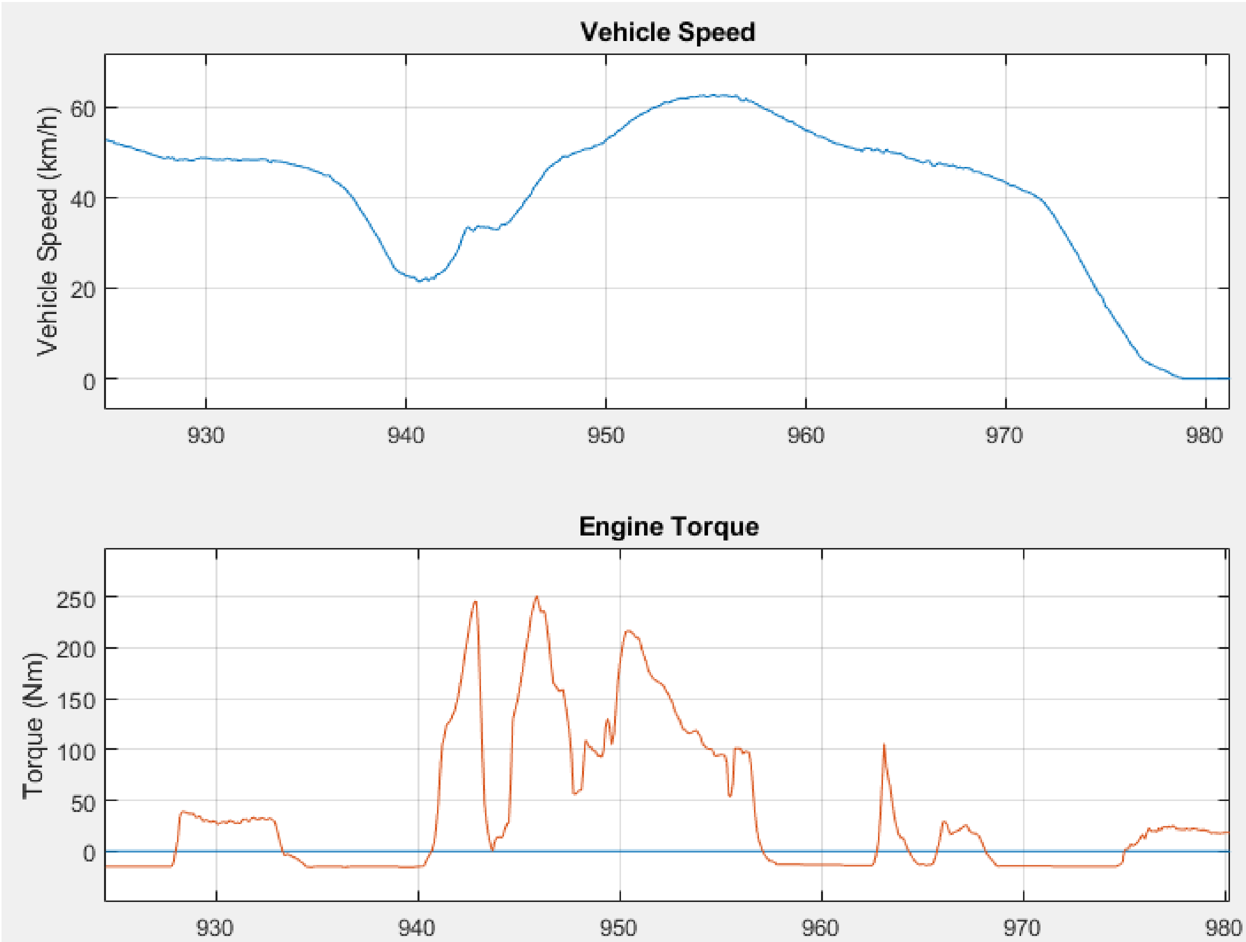

Figure 40: ICE Only acceleration 20-60km/h

4.1.2 Charge Sustaining

A hybrid vehicle without the ability to charge the HV battery externally through a charging port must be charge sustaining (CS) through regenerative braking to charge the HV battery. Charge sustaining is an operating mode in which the HV battery state of charge (SOC) may fluctuate but maintains an average range while driving. To maintain CS a motor penalty must be implemented. The motor penalty varies based on the current SOC and the target SOC. The motor penalty only affects the positive output torque of the EM. Negative torque values are calculated by the regenerative braking control module (RBCM), this output of regenerative torque is not affected by the charge sustaining calculation. The charge sustaining calculation only affects the output of positive torque from the electric motor.

The motor penalty (MP) factor ranges between -1 and 1. The motor penalty has a value of 1 as the SOC drops to a lower limit and -1 when the SOC approaches the upper limit. A motor penalty dead zone of 10% was implemented for when the SOC is within 45-55%, the MP is equal to 0. When the MP is implemented, the engine will operate off the OEL but this MP dead zone allows the Engine to operate on the OEL more often while the SOC is in a good range rather than the MP only being zero when the SOC is exactly 50%. Once the motor penalty is calculated it is multiplied by the torque support value (R). The torque support value is then added to the engine output torque thus changing the EM output as seen in Equation 4. The driver torque request is a constant in Equation 4. Equation 4 demonstrates how the motor penalty affects the engine torque output and the YASA torque output. If the SOC is at 50% and the motor penalty is zero, the engine will output the OEL torque, and the motor will out the remaining torque to reach the driver request torque but as the MP increases with dropping SOC the Engine torque increases thus lowing the required motor torque.

Equation 4: Motor Penalty Torque Added to Engine Torque

$$T_{Driver\_Request} = (T_{ICE\_OEL} + (MP * R)) + T_{EM}$$

Equation 5: Motor Penalty Calculation

$$MP = \frac{2}{1+e^{k(SOC_{Target}-SOC)}} - 1$$

The value k is a constant that dictates the curvature of this motor penalty, seen in Figure 41, with k values ranging from 0.3 to 1, demonstrating the change in curvature.

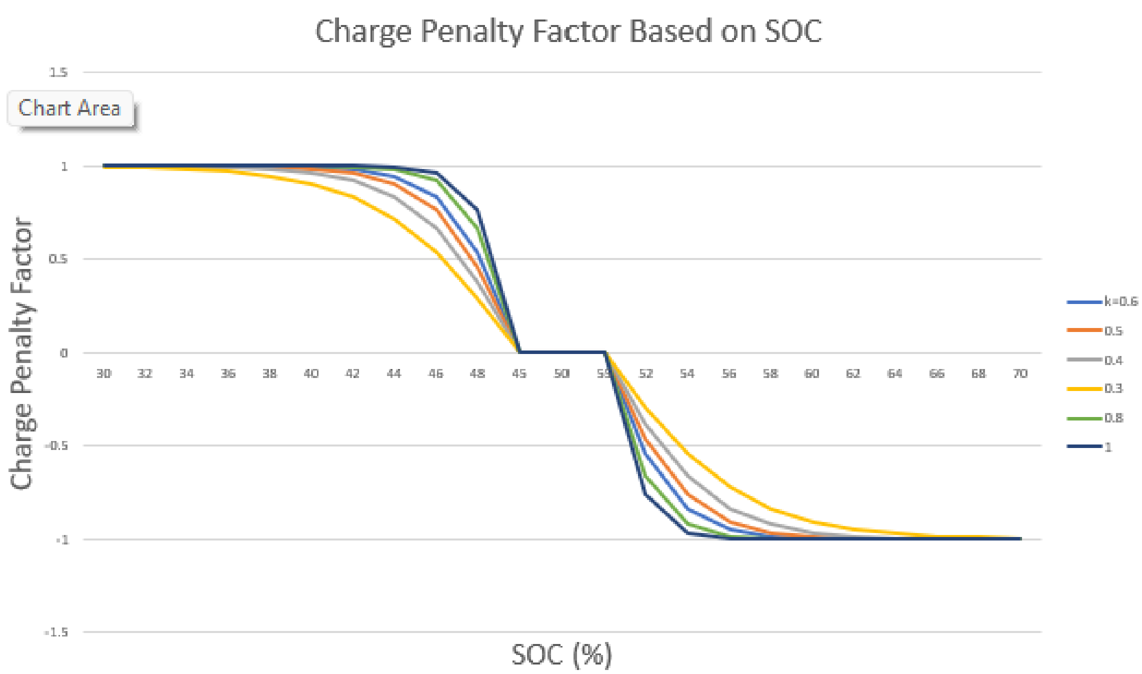

Figure 41: Motor Penalty Distribution Based on SOC and Varying k Values

The k and R values are constants that have been optimized to improve the CS of the HV battery while also improving the fuel efficiency. The k and R values were optimized in MIL, using improved fuel efficiency, and maintaining charge sustaining at the 2 parameters for optimization. Figure 42 shows the change in SOC over the EMC city drive cycle without the CS in place in MIL, the starting SOC of 50% and the final SOC was 46.34%.

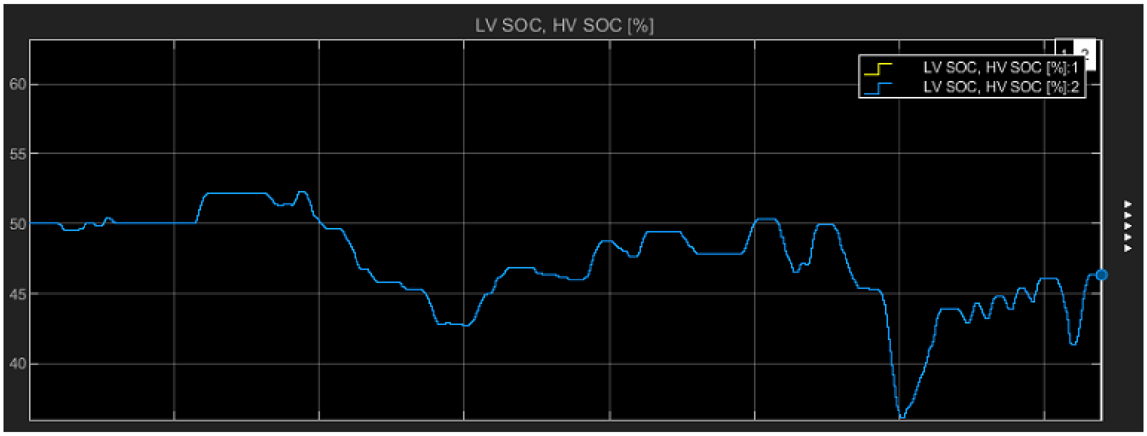

Figure 42: Change in HV SOC over ECM City Drive Cycle Without the MP

x-axis: 0-739 seconds, each vertical line is 100 seconds.

Figure 43 shows the change in SOC over the EMC city drive cycle with CS in place in MIL, the starting SOC of 50% and the final SOC was 53.03%.

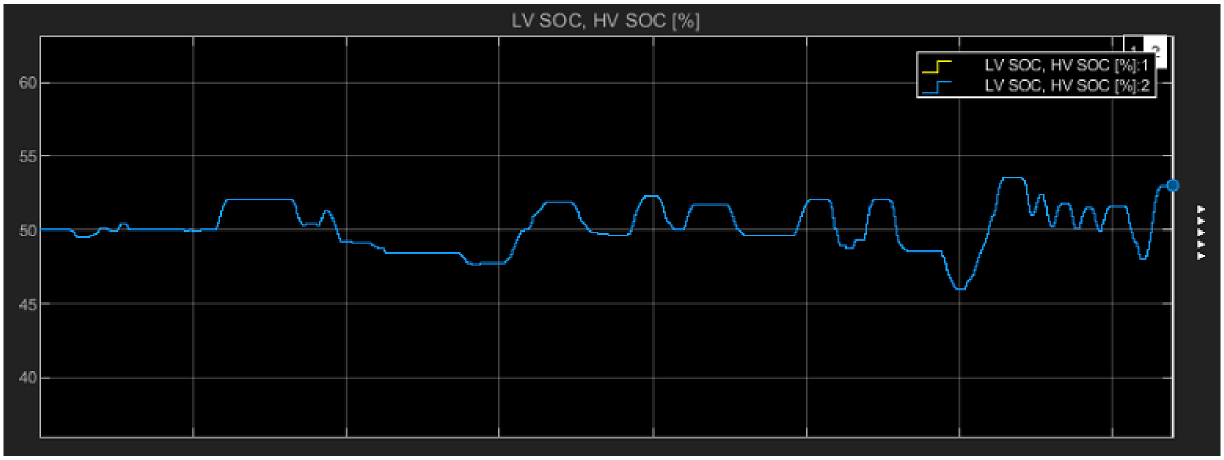

Figure 43: Change in HV SOC over ECM City Drive Cycle With MP Enabled

When charge sustaining is implemented, Figure 43, the deviation from 50% SOC over the full EMC city drive cycle is lower than that of Figure 42 when charge sustaining is not implemented.

This shows the charging penalty function working as it should. Vehicle logs also demonstrate the charge-sustaining algorithm operating as intended. Figure 44 demonstrates the SOC increase from starting at 41% increasing over the McMaster drive cycle to over 50%. Figure 45 demonstrates the decrease in SOC when starting at 60% and discharging to below 50% and ending the McMaster Drive cycle at just above 55%. This fluctuation is SOC is to be expected because driving condition vary but this charge sustaining algorithm is robust and adapts from drive cycle to drive cycle.

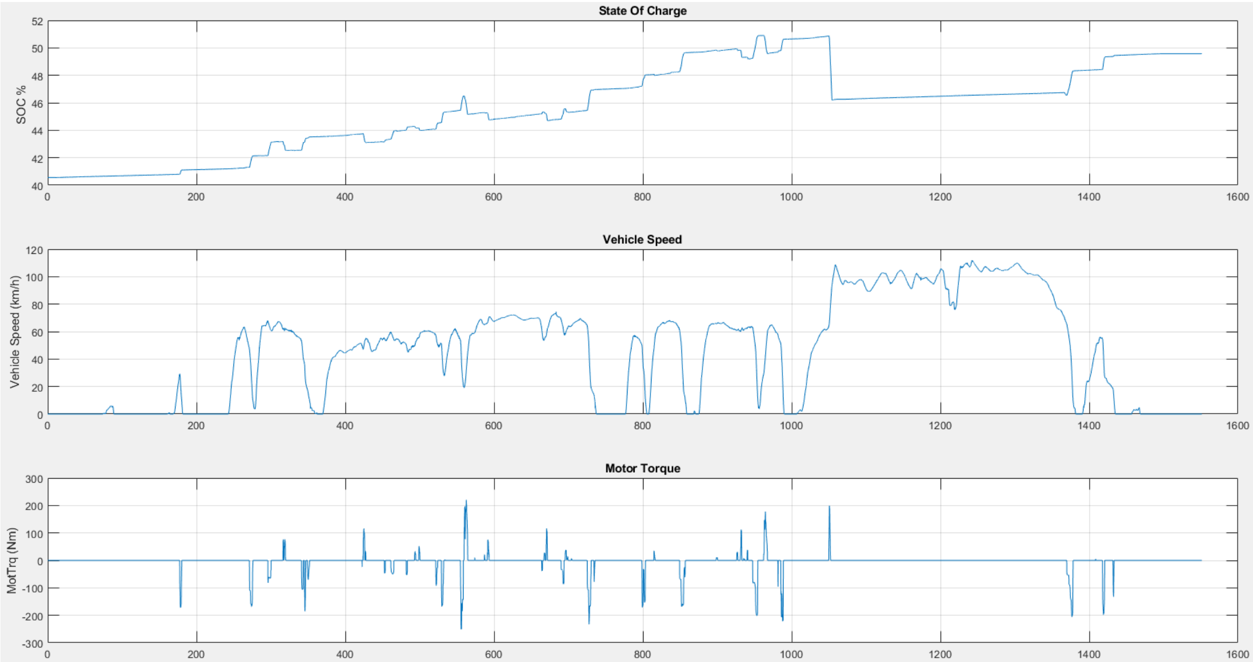

Figure 44: SOC Increasing Over a McMaster Drive Cycle

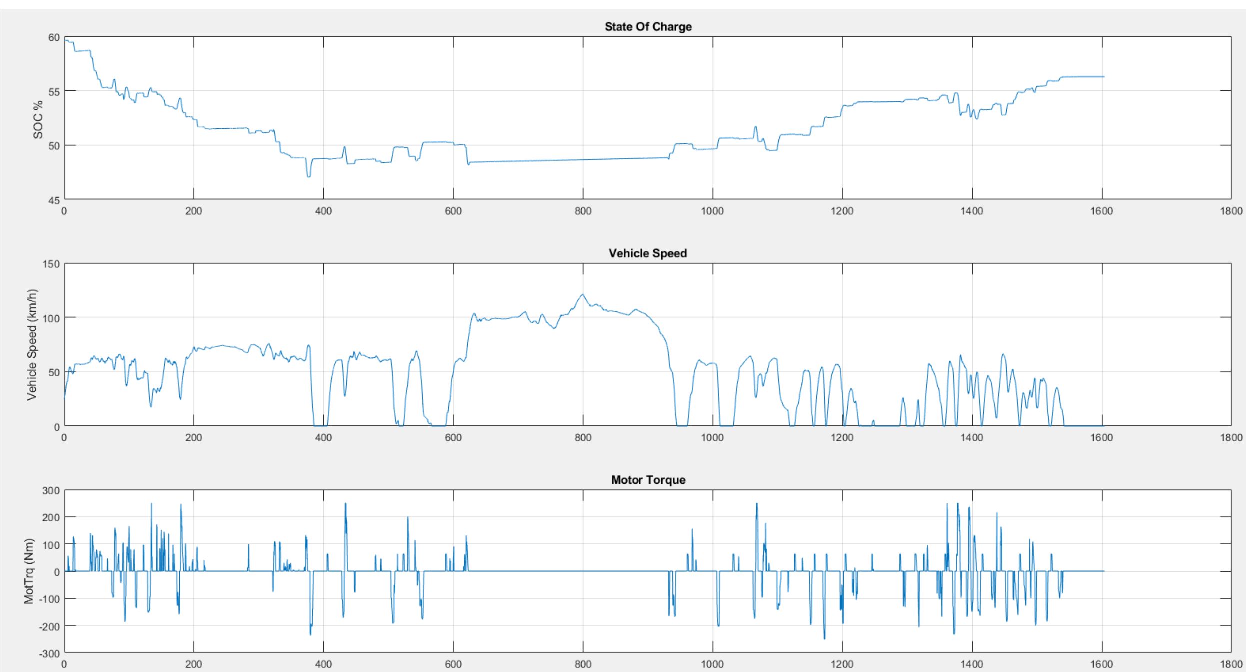

Figure 45: SOC Decreasing Over a McMaster Drive Cycle

4.2 Energy Management Strategy Implementation

4.2.1 Torque Split

The torque split algorithm centers around the driver's axle torque request also know as the wheel torque command. This request is determined based on a GM supplied pedal map that is used in stock vehicle engine control modules. This 2D look-up table has accelerator pedal position and current vehicle speed as its inputs and axle torque request as its output. The wheel torque command becomes an input into the torque split algorithm as seen in Figure 46.

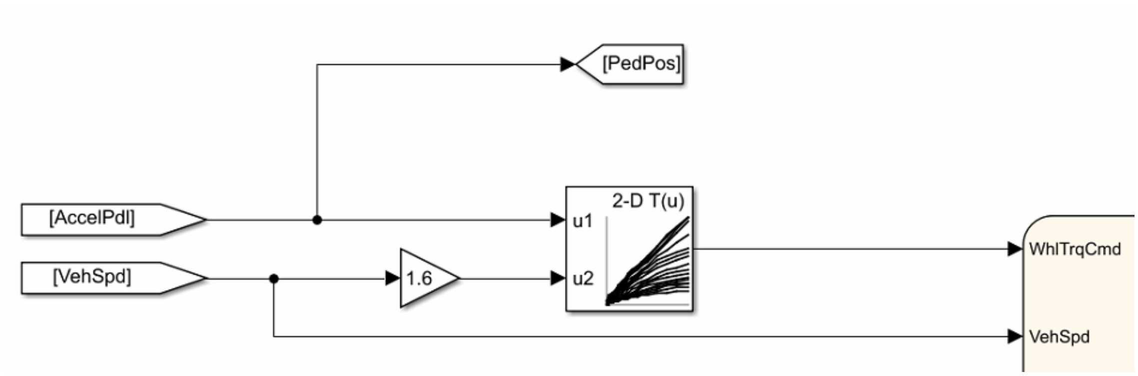

Figure 46: Stock GM Pedal Map

The axle torque request is denoted as WhlTrqCmd within the EMM and is converted to a wheel power command by multiplying the WhlTrqCmd and the wheel speed. Figure 47 shows the wheel power calculation. Torque can only be compared directly along the same drive shaft, or a 4-wheel drive vehicle the torque acting on the front and rear wheels can be added to determine the resultant torque acting on the vehicle. The advantage of using power to allocate torque to different components is the component power outputs are directly comparability, if the wheel power command is fulfilled by the YASA electric motor power output and the ICE power output, the drivers wheel torque command will also be fulfilled. Torque is not directly comparable unless it is along the same drive shaft, and this requires extra calculations using gear ratios to compare the EM torque and the ICE torque. The complexity of these calculations may lead to error. This is emphasized for the ICE due to the 9-speed transmission, the gear ratio between the ICE and the wheels is variable.

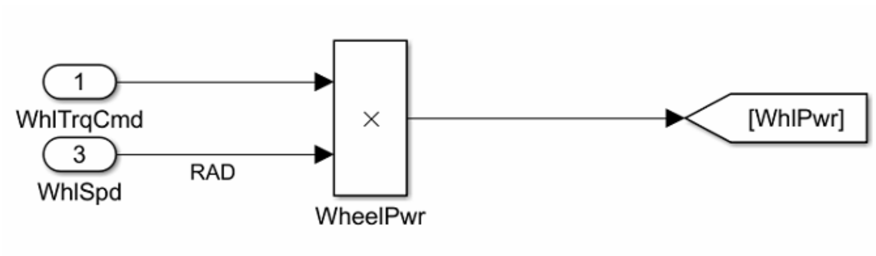

Figure 47: Wheel Torque Command Converted to Wheel Power Command

The sum of the ICE power request and the EM power request must always equal the wheel power command. The wheel power command is the target, and the ICE calculates its power command based on the OEL. Figure 48 demonstrates this calculation and circled in red is the addition of the motor penalty to maintain charge sustaining as seen in Equation 4.

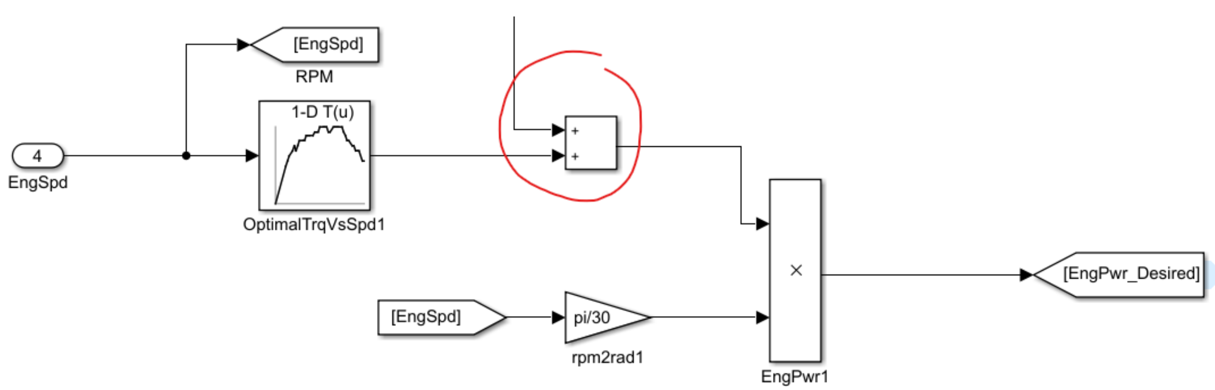

Figure 48: ICE OEL power calculation

The EM power is determined by the difference between the ICE OEL power, and the wheel power command as seen circled in red in Figure 49 and based on Equation 3. This EM desired power is compared to the limits of the EM. If the EM desired power is outside the EM limits the EM will operate at its limit and the remaining power will be added back to the ICE OEL power. This is to ensure the wheel power command is fulfilled at all power requests as seen in Figure 50.

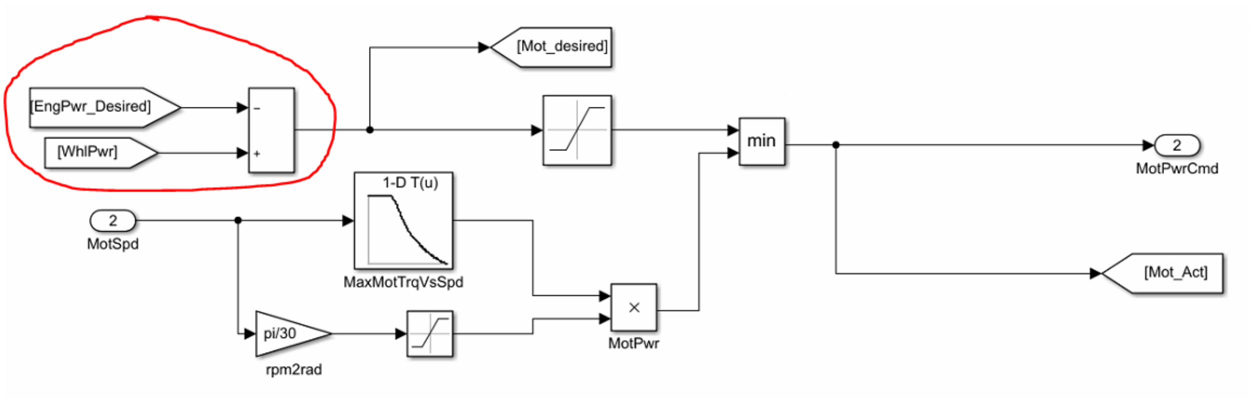

Figure 49: EM power calculations

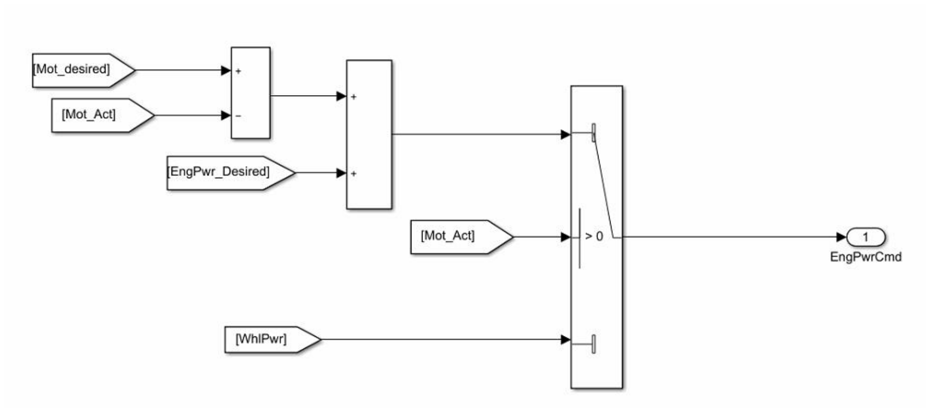

Figure 50: Final ICE power allocation

When the EM power request is 0 the ICE power request is equal to the wheel power command. The EM power request is 0 whenever the ICE OEL power is larger than the wheel power command. The EM shall not produce a negative torque unless the deceleration pedal is pressed. The ICE power command and the EM power command are both converted back to torque requests by dividing by their respective rotational speed.

4.2.2 Charge Sustaining/ Motor Penalty

Figure 51 shows the addition of the motor penalty to the ICE OEL power command when the motor penalty ranges from negative values to positive values. Negative values occurs when the SOC is larger than the target SOC, reducing the ICE OEL power command and increasing the EM power command. Positive values occur when the SOC is below the target SOC, increasing the ICE OEL power command and reducing the EM power command.

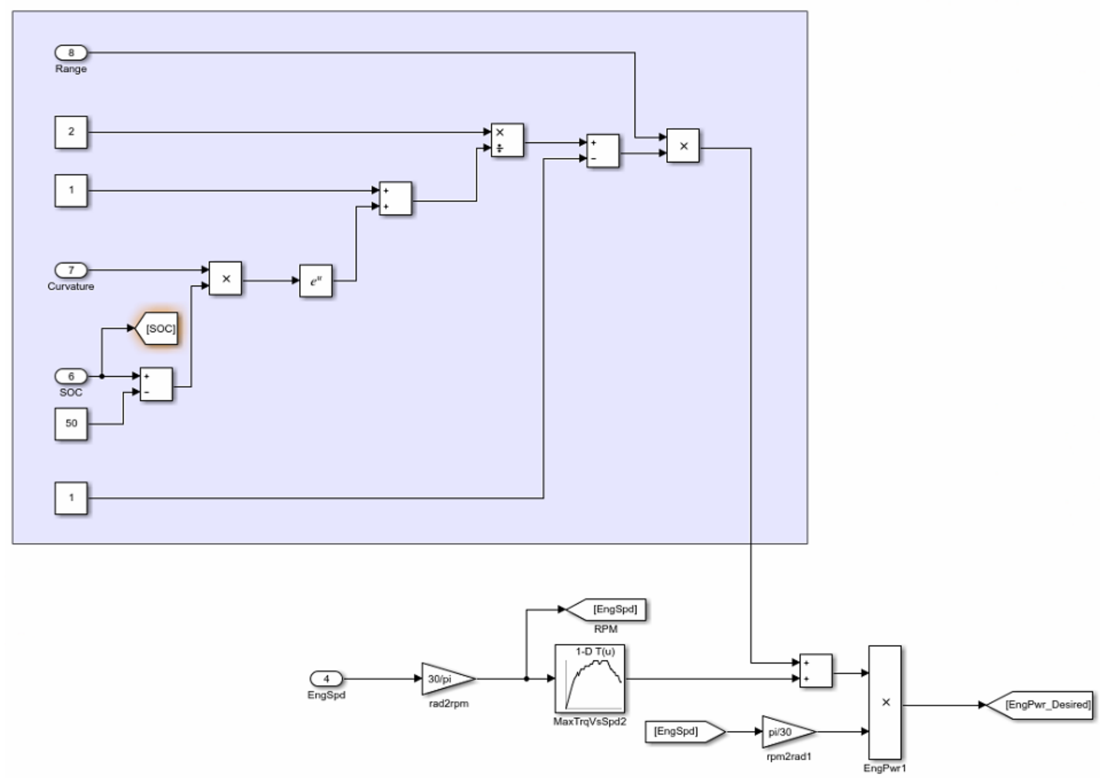

Figure 51: Motor Penalty Calculations

These calculations dictate component torque split when the EMM is in the torque split state of the EMM Stateflow, during a standard drive cycle this is the operating state for the majority fo the time.

4.2.3 High Acceleration State

The high acceleration state is triggered when the driver has the accelerator pedal above 85%, when this state is triggered, it is clear that the driver desires high acceleration and the method for torque determination of the ICE no longer using the OEL but utilized the maximum engine torque vs speed look up table for maximum acceleration from the engine. The motor utilizes a similar method for determining its torque output, using a maximum motor torque vs speed look up table but with 2 added penalty factors that takes component limits into account, both are limits of the battery. During high torque operation of the motor, the current draw from the battery causes the voltage of the HV battery to drop to a point where an under-voltage fault after only a few seconds of maximum toque output of the motor. The battery voltage is the first scaling factor that limits the battery during high acceleration events, a linear scaling factor that begins with full output when the HV battery voltage is 290 volts and drops to zero output if the HV battery voltage drops to 260 volts. The second limiting factor is vehicle speed, the higher the vehicle speed the higher the motor power required to output torque, motor power is motor speed multiplied by motor torque, the higher motor speed (Vehicle speed) the higher the current draw from the HV battery. Another linear motor penalty is used based on vehicle speed to limit motor torque output during full torque output form 0 km/h to 70km/h but linear decline to 0 torque output at 80km/h, this same limiting factor is used in the torque split state. When the vehicle reaches 80km/h the motor stops outputting torque and the clutch opens to limit the motor free wheeling at high speeds. The clutch closes when vehicle speed drops back to 70km/h. The gap of 10 km/h was chosen to limit the rapid opening and closing of the clutch that occurred during early VIL testing with a smaller speed buffer. Figure 52 shows the High Acceleration State torque calculations based on the motors maximum torque vs speed curve and the engine maximum torque vs speed curve.

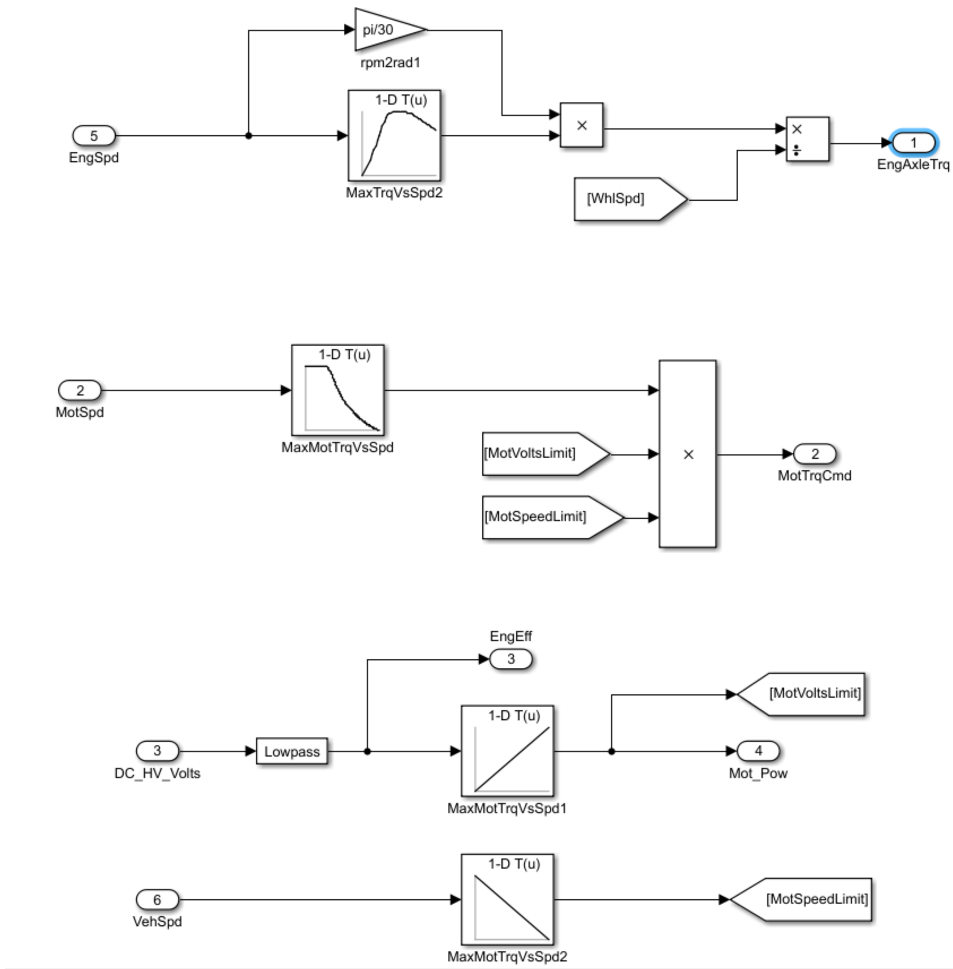

Figure 52: High Acceleration State

4.3 Engine Control Module

The Engine Control Module was developed during chassis dyno and VIL testing, as discussed in chapter 4. The Engine Control module enables the ACC mode of the MAC Team vehicle engine, allowing for torque split functionality of the vehicle. Engine torque requests calculated by the EMM will be honoured by the engine. Figure 53 shows the EMM and ECM on the top level of the vehicle control system.

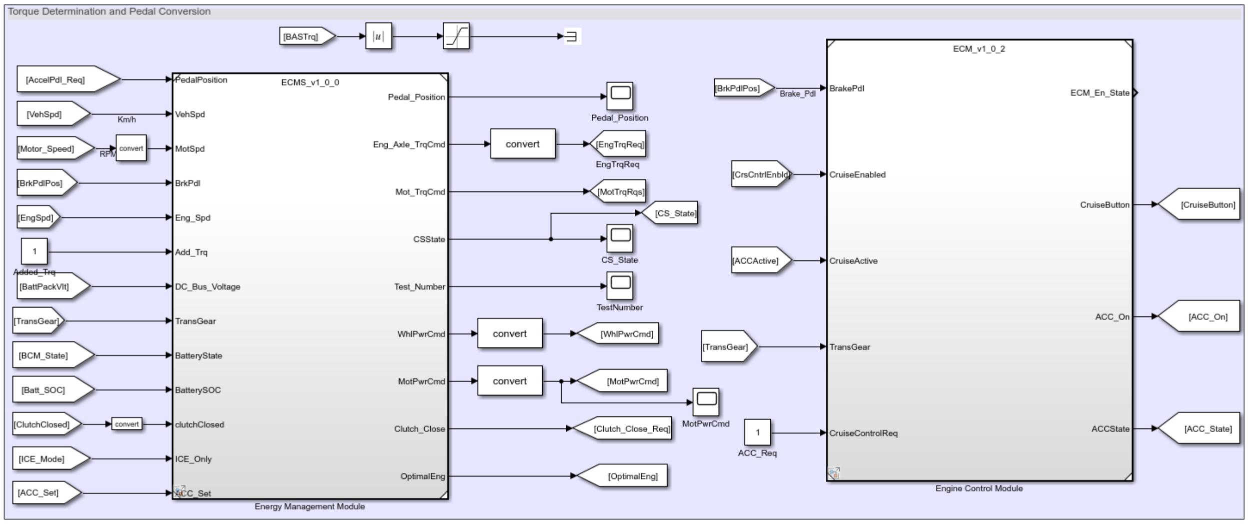

Figure 53: EMM & ECM Top level of vehicle control system

4.4 Battery Control Module

The BCM was developed through the HEV4 battery pack test bench described in section 3.2.2. The BCM enables high voltage within the MAC Team vehicle. Figure 54 displays the BCM at the top level of the vehicle control system.

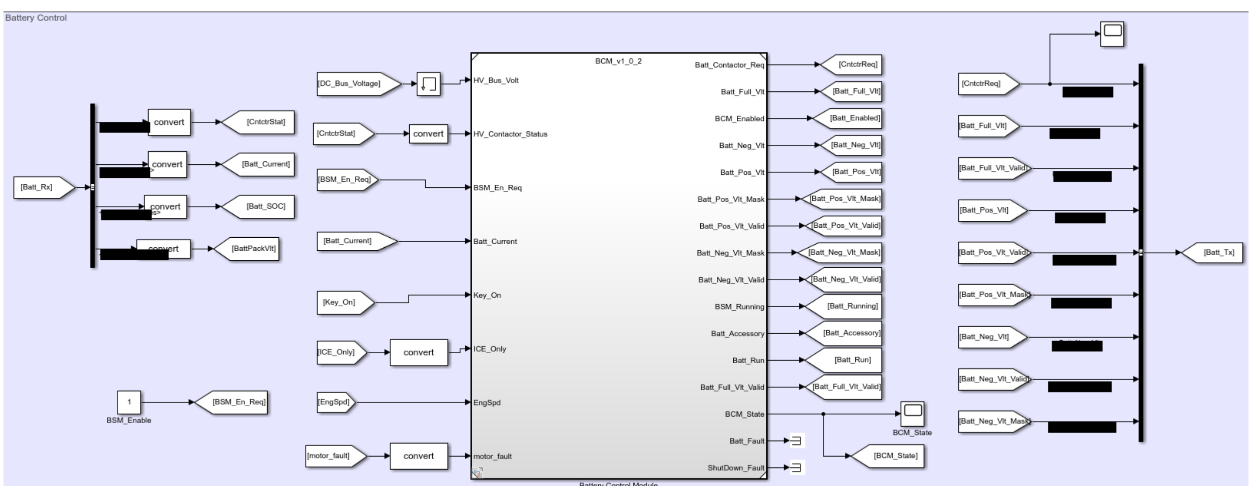

Figure 54: BCM top level of vehicle control strategy

4.5 BAS Control Module (BASCM)

The BAS control module was developed through the BAS test bench, described in chapter 4, and finalized during VIL testing. The BASCM operates in generator mode only, there were 2 generating settings, high charge setting and low charge setting. When the low voltage battery had low voltage below 11.5 volts, high charge setting of 5 Nm was established to charge the LV battery back to operating levels, if the high charge setting over charged the LV battery to above 15 volts the setting would drop to 3.5Nm charging. This level of charging was seen a necessary to operate the MAC team vehicle due to the added components drawing power from the LV battery and with the Rinehart being packaged in the rear of the vehicle there was a voltage drop seen by the Rinehart of about 1.5 volts. Maintaining good voltage levels of the LV battery was very important to maintain proper operation of the Reinhart motor controller and by extension the YASA electric motor. As the vehicle speed increase the charging power would increase and over charging could become a potential issue while operating the vehicle at moderate to high speeds, the Valeo iStars BAS has internal logic that will limit its torque output based on the voltage of the battery and the speed of the BAS. Figure 55 demostrates this function. Figure 55 shows the magnitude of the BAS torque dropping as the vehicle speed is increasing over the McMaster drive cycle. This over charging affect that drops the regenerative torque of the BAS has an added benefit of reducing the resistance of the BAS on the engine at higher speeds.

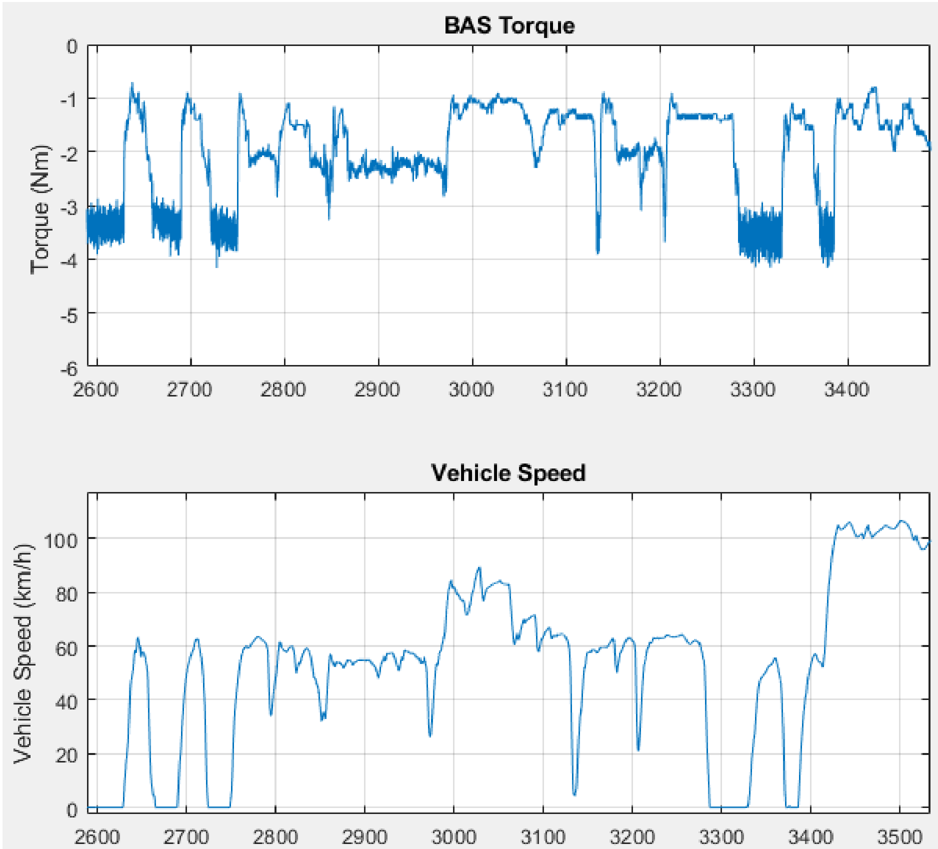

Figure 55: BAS Regenerative Torque Decrease as Vehicle Speed Increases

4.6 Motor Control Module

The MCM was developed through the YASA test bench, the chassis dynamometer testing and finalized during on-road testing. The motor control module has implemented a speed mode control in addition to the existing MCM used throughout the test bench and initial VIL testing. This addition was required in order to couple the MCM and the clutch control module (CCM). The MCM is coupled with the clutch control module through YASA speed mode switching. The CCM initiates the speed mode switch when the clutch wants to close while the vehicle is at speed. The YASA bench testing did test speed mode and torque mode but the in vehicle testing added a level of complexity to speed match with the clutch for smooth closing of the clutch at high speed. Due to this added complexity three states were added to the MCM for clutch speed matching. High Speed clutch open state, motor speed mode idle state and clutch speed match state. Figure 56 shows the added speed mode states to the MCM.

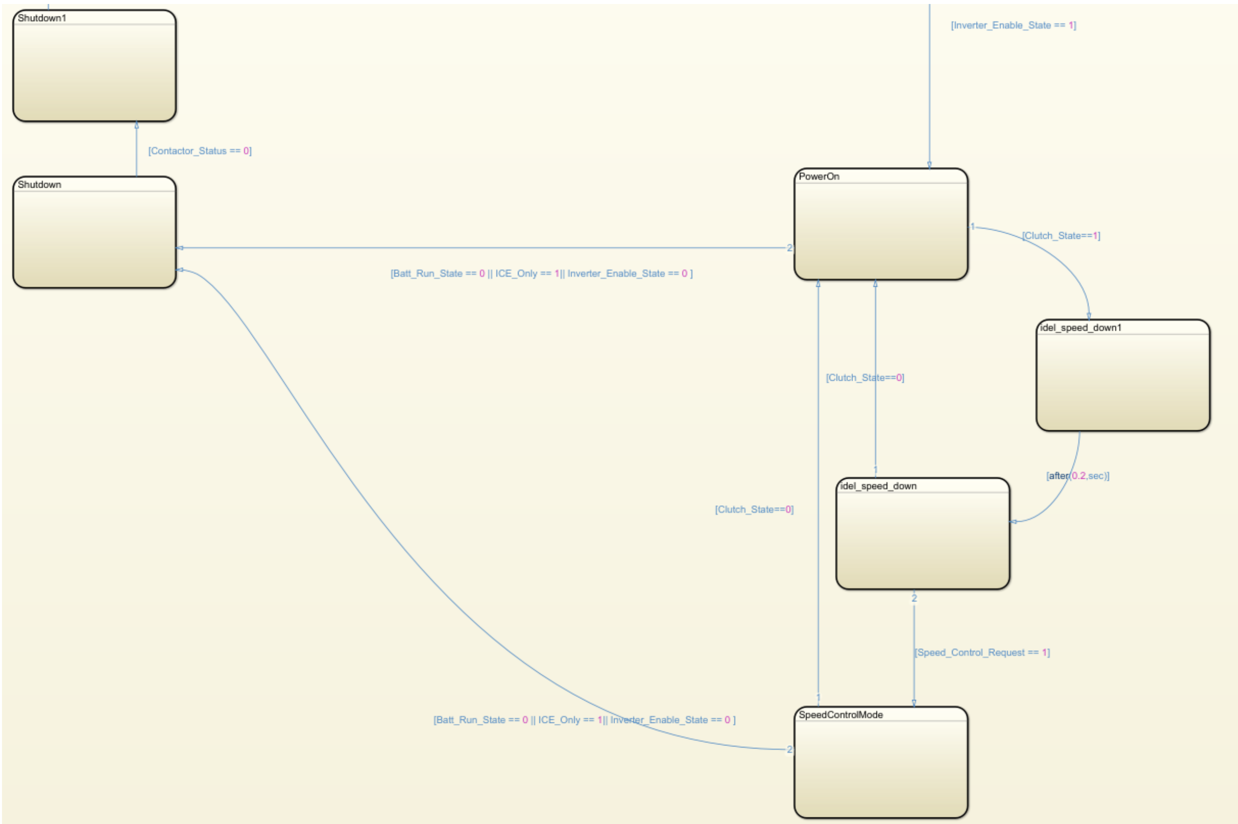

Figure 56: MCM Speed Mode Stateflow

High Speed clutch open state initiates when an open clutch signal is sent from the clutch hardware through a digital signal. At high speeds the clutch opens due to the vehicle reaching 80km/h, by the time the vehicle reaches 80km/h the motor is outputting very limited torque due to the component limitations incorporated in the EMM. To ensure smooth opening of the clutch, the motor switches to speed mode and matches the clutch speed. Once the clutch opens the motor enters a waiting state with an output speed 0 RPM. The motor speed mode idle state is the state that sends the speed command of 0 to the motor. This state transitions to the clutch speed match state when a signal is received from the clutch control module requesting a speed match for the clutch to close. While the vehicle is operating at high speeds this command is sent when the vehicle speed drops to 70km/h after a high speed section of a drive cycle. The clutch speed match state sends a speed request to the motor to match speeds with the clutch. Using gear ratios from the wheels to the clutch and from the motor to the clutch. The motor accurately match these speeds during operation of the vehicle. Once the difference between the clutch plates is within 250 RPM the clutch close request is sent from the Clutch control module and upon closing the MCM transitions back to the PowerOn state where torque mode is initiated and torque requests resume. Figure 57 shows the YASA speed match while decelerating from a high-speed section of the McMaster drive cycle. The speed match occurs when the vehicle reaches 70km/h, and upon closing the YASA regenerative brakes to regain as much energy as possible through out a drive cycle.

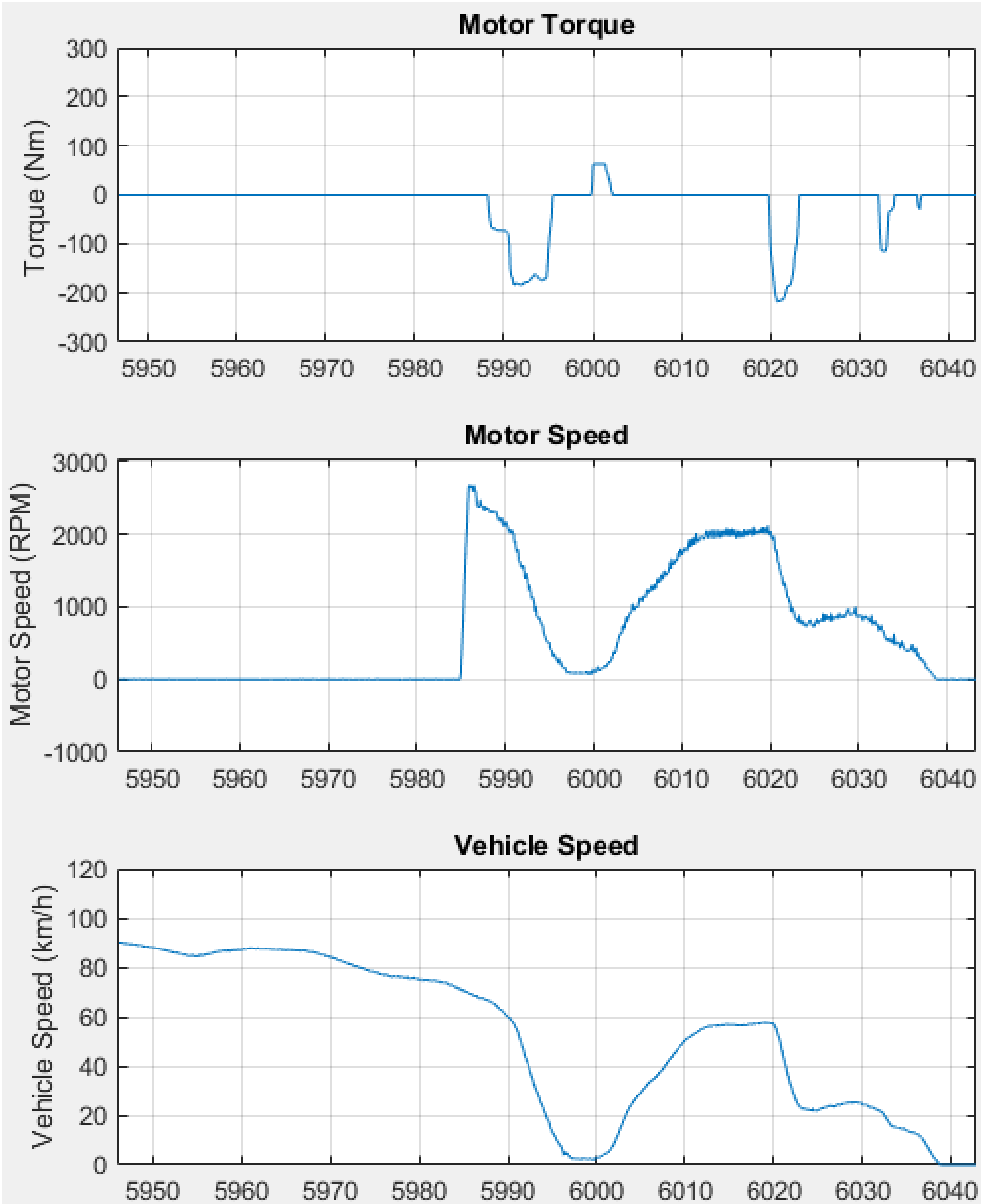

Figure 57: VIL Motor Speed Matching

4.7 Clutch Control Module

The CCM was developed through dynamometer testing, VIL testing and on-road testing. The clutch control module is responsible for opening and closing the clutch while maintaining comfortable driveability while doing so. The CCM consists of two state flows, the first state flow called the clutch enable request state flow was used to determine if the clutch should be open or closed and the second state flow is for implementing the decision to open or close the clutch, this state flow is called the clutch speed matching state flow. The clutch enable request state flow operates on three inputs.

- High Voltage Contactors Status [0-2]
- Transmission Gear [0-14]
- Vehicle Speed [km/h]

The clutch enable request state flow default state is to keep the clutch open until the HV battery contactors have been closed, the motor is ready to operate, and the vehicle is not in reverse. Once the clutch has been closed, vehicle speed becomes the next check to open the clutch if the vehicle speed increases above 80km/h a clutch open signal is sent to the clutch speed matching state flow. When the vehicle speed falls below 70km/h a clutch close signal is sent to the clutch speed match state flow. Figure 58 shows the clutch enable request stateflow within the clutch control module.

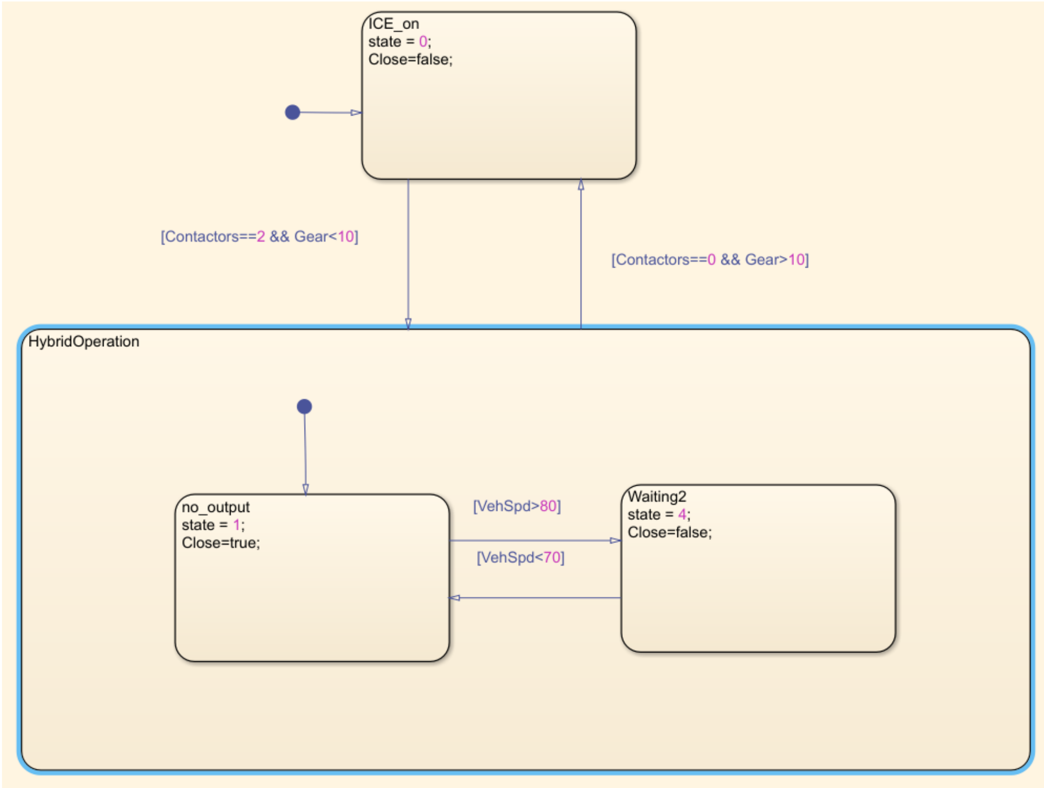

Figure 58: Clutch Enable Request Stateflow

The clutch speed match state flow is responsible for sending the close/open signal to the clutch hardware and with sending speed matching commands to the MCM. The state flow begins in a neutral state with the clutch open, once a clutch enable request comes in speed checks are performed and motor speed match signals are sent to the MCM if the speeds are not already matched, if the vehicle is stopped the speed checks pass instantly and the clutch closes. If the vehicle is at speed the speed match signal is send to the MCM and once the difference in speed between the clutch plates are less than 25RPM for 0.2 seconds, the close clutch signal is sent to the clutch hardware. Once the clutch has been closed the state flow is in a waiting state for the next open clutch signal. Figure 59 shows the clutch speed match state flow.

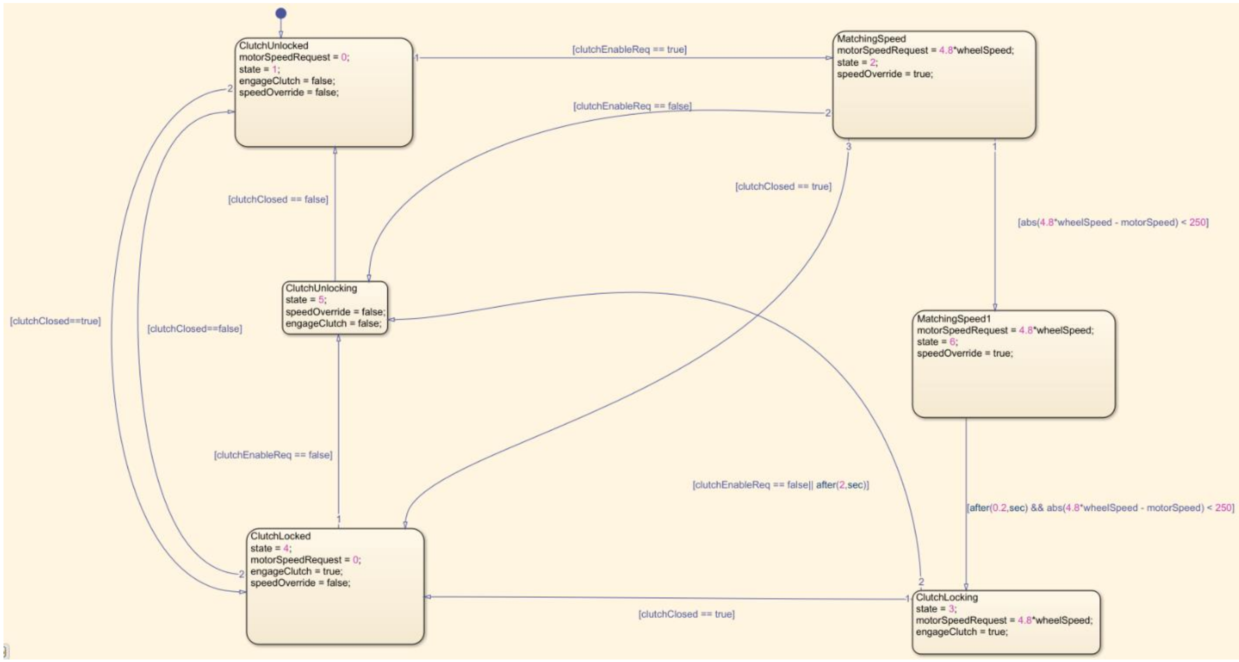

Figure 59: Clutch Speed match Stateflow

4.8 Regenerative Braking Control Module

The RBCM was developed in MIL, through simulation to determine an effective regenerative braking strategy that maximized regenerative braking while maintain driveability. The RBCM is responsible for determining the negative torque output of the motor during braking events. This module utilizes parallel regenerative braking, a method in which the mechanical disc brakes continuously supply brake force when the driver is applying the deceleration pedal and the EM supports the disc brakes by applying negative torque to the wheels. The amount of negative torque the EM produces is based upon the maximum available negative torque at the current EM rotational velocity adjusted by a scaling factor for smoother regenerative braking leading to better driveability. This scaling factor takes into account vehicle speed, HV battery state of charge (SOC) and the deceleration pedal position. Regenerative braking is limited below 15km/h and 0 below 10km/h, regenerative braking is also reduced when the SOC of the HV battery is above 70%. Braking events where the brake pedal is pressed above 33% full regenerative braking is requested, this metric was used to maximize the amount of energy recuperated through out a drive cycle as it is very rare for the brake pedal to exceed 50% unless for an emergency braking event, in that case regenerative braking is a very useful function. Figure 60 shows the negative torque calculation being made in the RBCM.

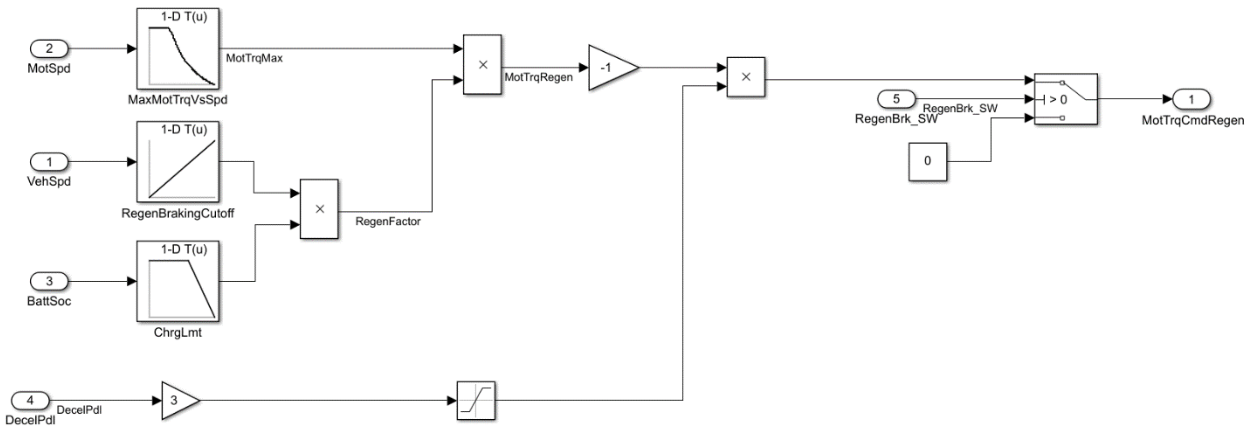

Figure 60: RBCM regenerative braking calculation

4.9 Gateway Interface Module

The gateway interface module is responsible for sending CAN messages to the hardware engine control module in the vehicle, since the ECM was removed for the stock GM High Speed LAN CAN bus, this module is responsible for every message that is altered between the GM HS and the ECM CAN bus, all GM HS CAN messages must be sent to the ECM and the majority of these messages do not need to be changed. This module is coupled with the software ECM responsible for establishing control of the ICE. There are a total of 5 CAN messages that are modified in this module.

4.10 Indicator Board Control Module

The indicator board is a control board located at the front of the vehicle with switches that the driver controls and lights to convey information to the driver. The switches consist of an ICE only switch, and a regenerative braking enable switch. The ICE switch is the most influential switch throughout the Vehicle Control System, directly impacting the EEM, BCM, MCM and indirectly the RBCM and CCM. The EEM would only send ICE torque requests when ICE_Only was enabled and the motor torque request would be equal to zero. The BCM would not allow the battery contactors to close or if the contractors were already closed an open request would be sent. The MCM would begin its shutdown process in coordination with the BCM if the MCM was in its power on state. The RBCM calculates the regenerative torque request during braking events, this regenerative torque is filtered through the MCM. The ICE_Only switch causes the motor torque to be equal to zero regardless of regenerative torque or acceleration torque. The CCM opens the rear clutch when the High Voltage Battery pack contactors are open, and the ICE switch causes the BCM to open the contactors.

The regenerative braking enable switch directly impacts the RBCM, when the regenerative braking enable switch is in the off position the RBCM outputs a regenerative torque equal to 0. There are 2 lights on the indicator board that convey important information to the driver, the first light is the engine control light, this light operates in coordination with the ECM, when control of the engine is confirmed the light becomes solid but if the control of the engine fails the light will flash. The second light is the HV battery light. The HV battery light flashes during close request and becomes solid when the contactors are closed and torque requests from the motor are enabled. Extra switches on the indicator board were utilized during development of VIL troubleshooting, the clutch open/close button was utilized while the CCM was being developed as an example.

4.11 CAVs Control Module

The CAVCM is responsible for establishing control of torque requests during CAV enabled operation, the module was developed by the MAC CAVs team. This module attempts to implement a MAC Team designed adaptive cruise control algorithum. This module was able to control the vehicle on multiple occasions during closed track testing but was never implemented for on-road VIL testing.

4.12 Summary

Through out the vehicle control system there are 10 control modules, 6 CAN buses, 5 analog I/O and 15 digital I/O. The EMM is the center piece of the vehicle control system, controlling the torque outputs of the ICE and EM. The EMM uses the optimal efficiency line of the ICE to request fuel efficient torque outputs from the engine, using the EM to support these requests all while maintaining charge sustaining operation of the HV battery. The ECM enables the ACC mode of the MAC Team vehicle engine, allowing for torque split functionality of the vehicle. The BCM enables high voltage within the MAC Team vehicle. The BASCM maintains the low-voltage system of the vehicle. The MCM controls the YASA in torque and speed modes. The CCM was developed to open and close the clutch without affecting the drivability of the vehicle. The RBCM dictates regenerative braking, gaining energy for the high-voltage battery while maintaining driveability. The gateway interface module maintains communication of the stock GM systems. The indicator board control module gives the driver control of the high voltage system. The CAVCM determines MAC Team designed adaptive cruise control algorithms. Theses modules worked in unison to operate the MAC Team vehicle for over 1500km of on-road driving.

Chapter 5

Performance Evaluation

The MAC Team Vehicle's has accumulated over 1500km of on-road hybrid driving. The MAC Team Vehicle's performance will be evaluated using four metrics: HV charge sustaining, vehicle fuel efficiency, vehicle driveability and vehicle reliability. Four different drive cycles will be used to evaluate these metrics, a high charging cycle with a starting SOC of 40%, a high discharging cycle with a starting SOC of 60%, a long hybrid drive which consists of 9 McMaster drive cycles a total of 183km and a long engine only drive which consists of 5 McMaster Drive cycles a total of 117km.

The McMaster Drive cycle was the standardized drive cycle that was used for the majority of on road testing. Figure 62 shows the McMaster drive cycle through Hamilton, Ontario and its 5 sections: A, B, C, D, and E. Figure 61 shows a CAN message log of the MAC Team vehicle speed over a single McMaster drive cycle with each section shown in red. The route begins at the McMaster Automotive Research Center (MARC) and leads to downtown Hamilton, being very densely populated with pedestrians, stop lights and other vehicles (Section A). It then takes us up the mountain to the upper, more residential area of Hamilton (Section B). After driving through the less congested part of city in uptown Hamilton (Section C), to then turn onto the highway (Section D) with a 90km/h speed limit. We merge onto the 400 series highway at 100km/h for our final stretch (Section E) before returning to the starting point at the MARC.

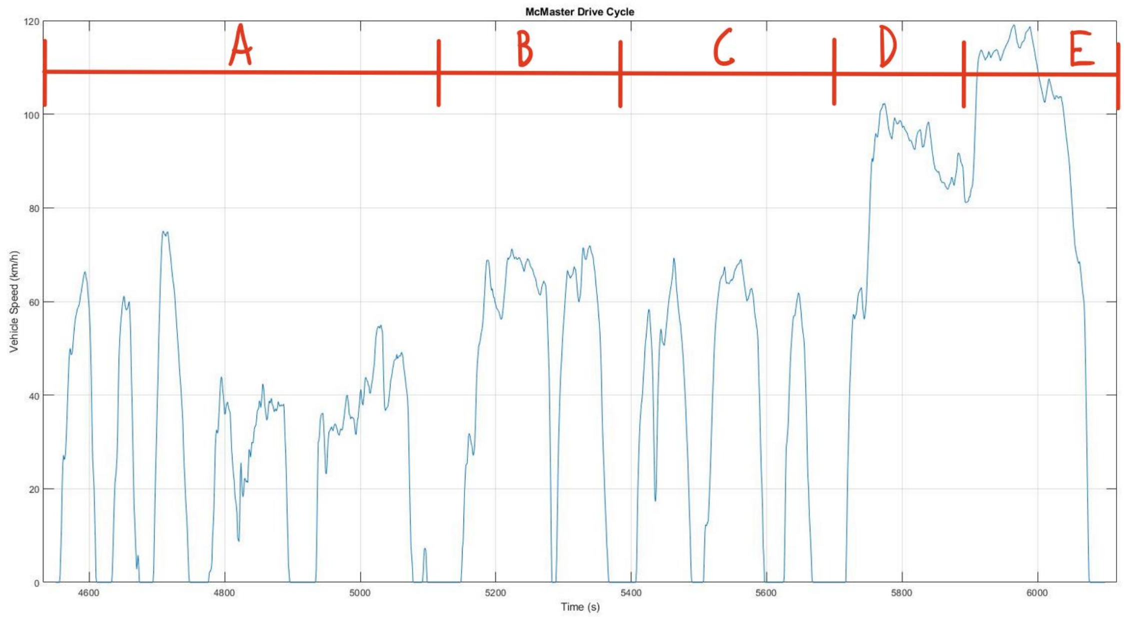

Figure 61: McMaster Drive Cycle Vehicle Speed CAN Log

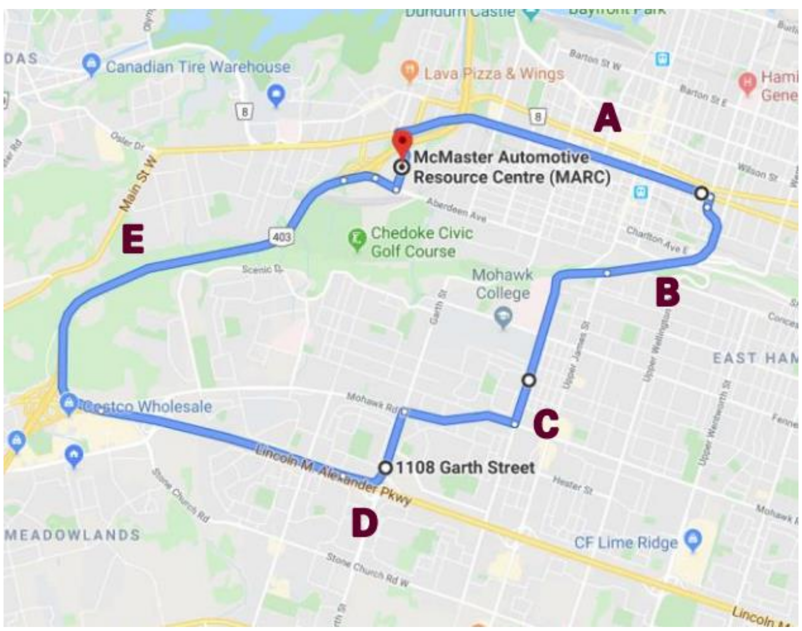

Figure 62: McMaster Drive Cycle Through Hamilton, Ontario

5.1 Performance Evaluation Drive Cycles

5.1.1 High Charging Cycle, 40% SOC Start

The high charge cycle consists of a single McMaster Drive cycle, with a starting SOC of about 40%, Figure 63 shows the drive cycle and the battery SOC.

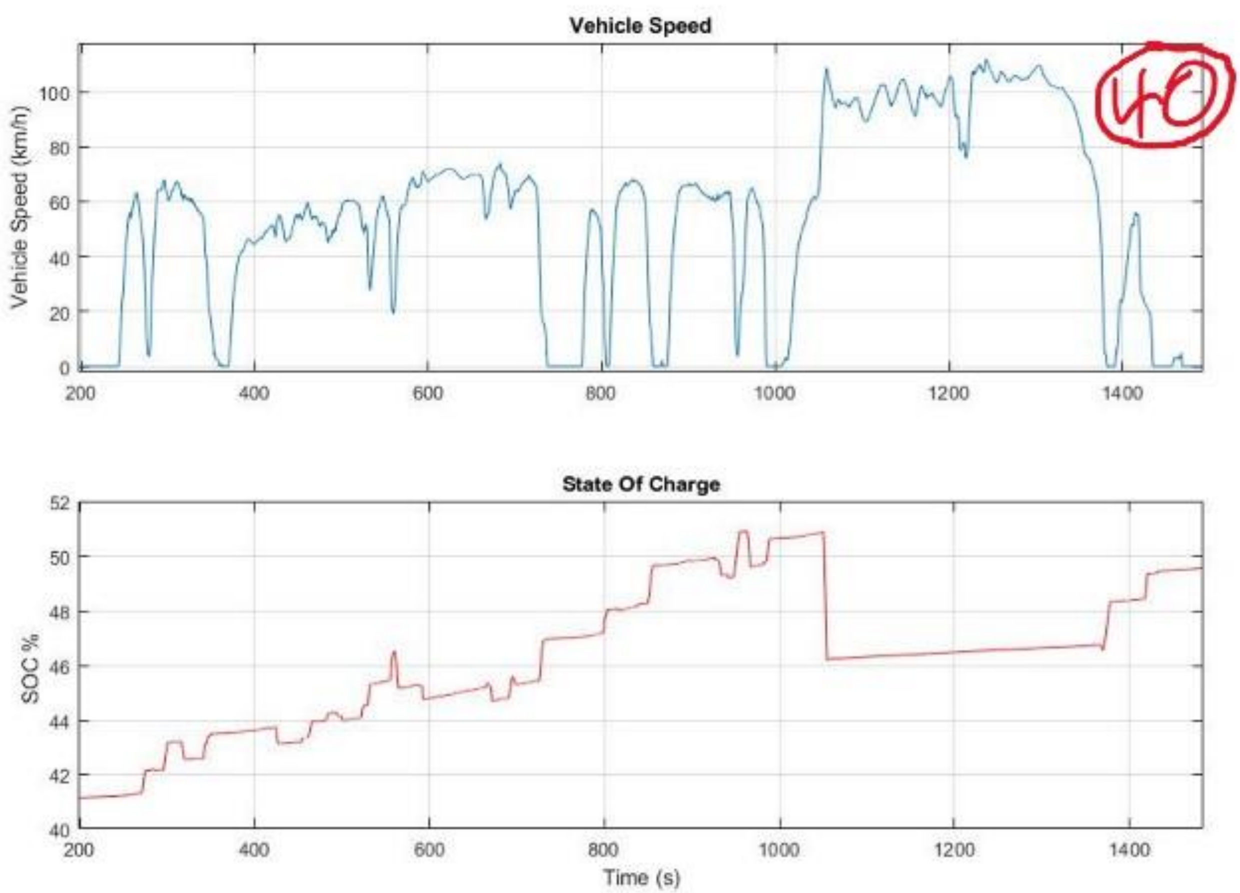

Figure 63: 40% SOC McMaster Drive Cycle

5.1.2 High Discharge Cycle, 60% SOC Start

The high discharge cycle consists of a single McMaster drive cycle, with a starting SOC of about 60%, Figure 64 show the drive cycle and the battery SOC.

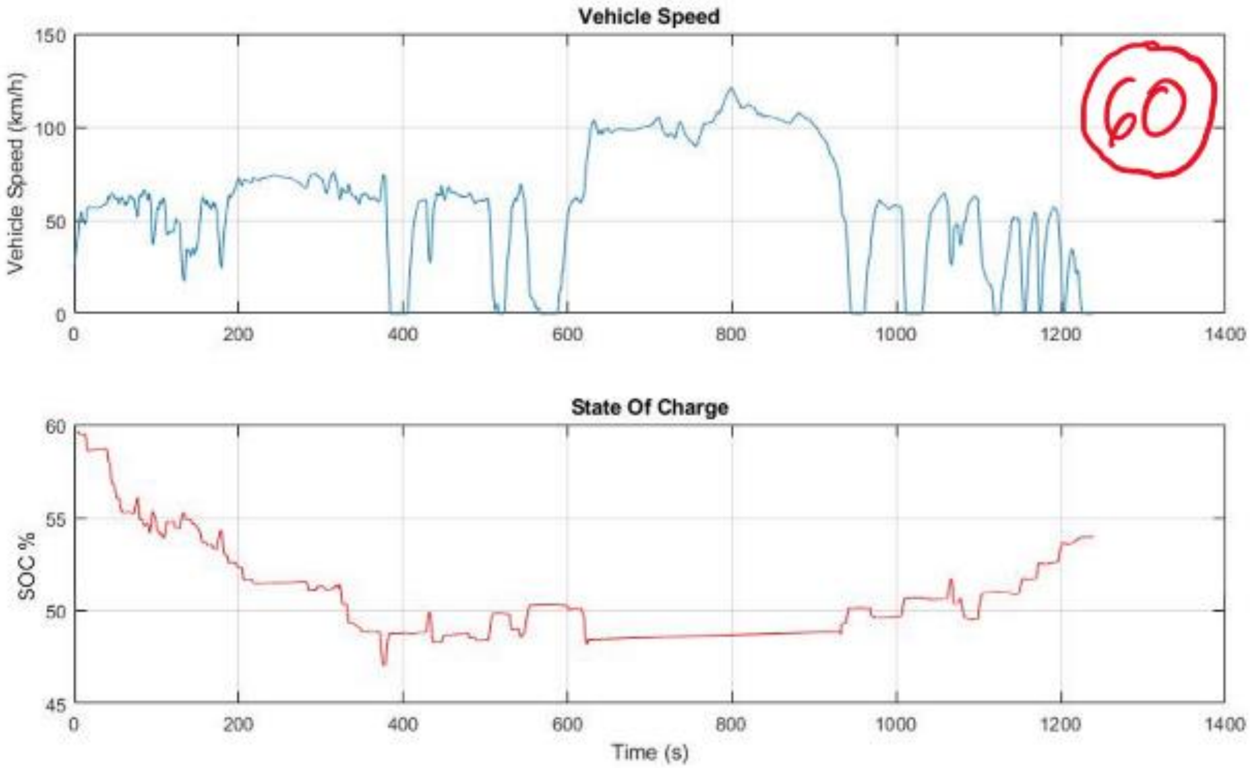

Figure 64: 60% SOC McMaster Drive cycle

5.1.3 Long Hybrid

The Long hybrid cycle consists of 9 McMaster drive cycles, Figure 65 shows the first 5 McMaster drive cycles and the steady state voltage change. Figure 66 Shows the next 4 McMaster drive cycles and the steady state voltage. The steady state voltage of the battery is directly proportional to the SOC. 50% SOC is represented by a steady state voltage of 295V.

Figures 67 & 68 show this direct proportionality between steady state voltage and SOC, using the 40% SOC charge cycle and 60% SOC discharge cycle as examples.

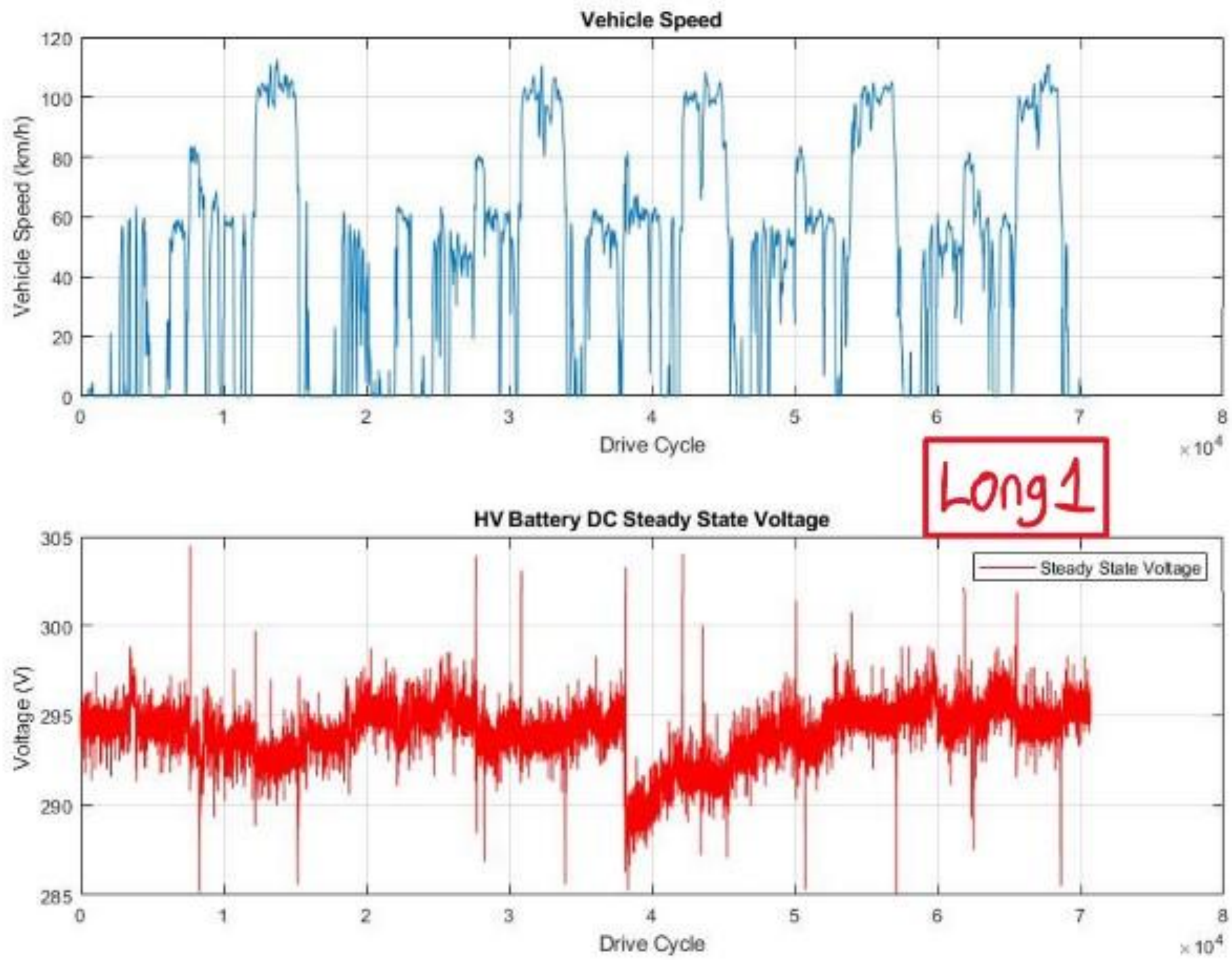

Figure 65: First 5 McMaster drive cycles and the change in Steady state voltage

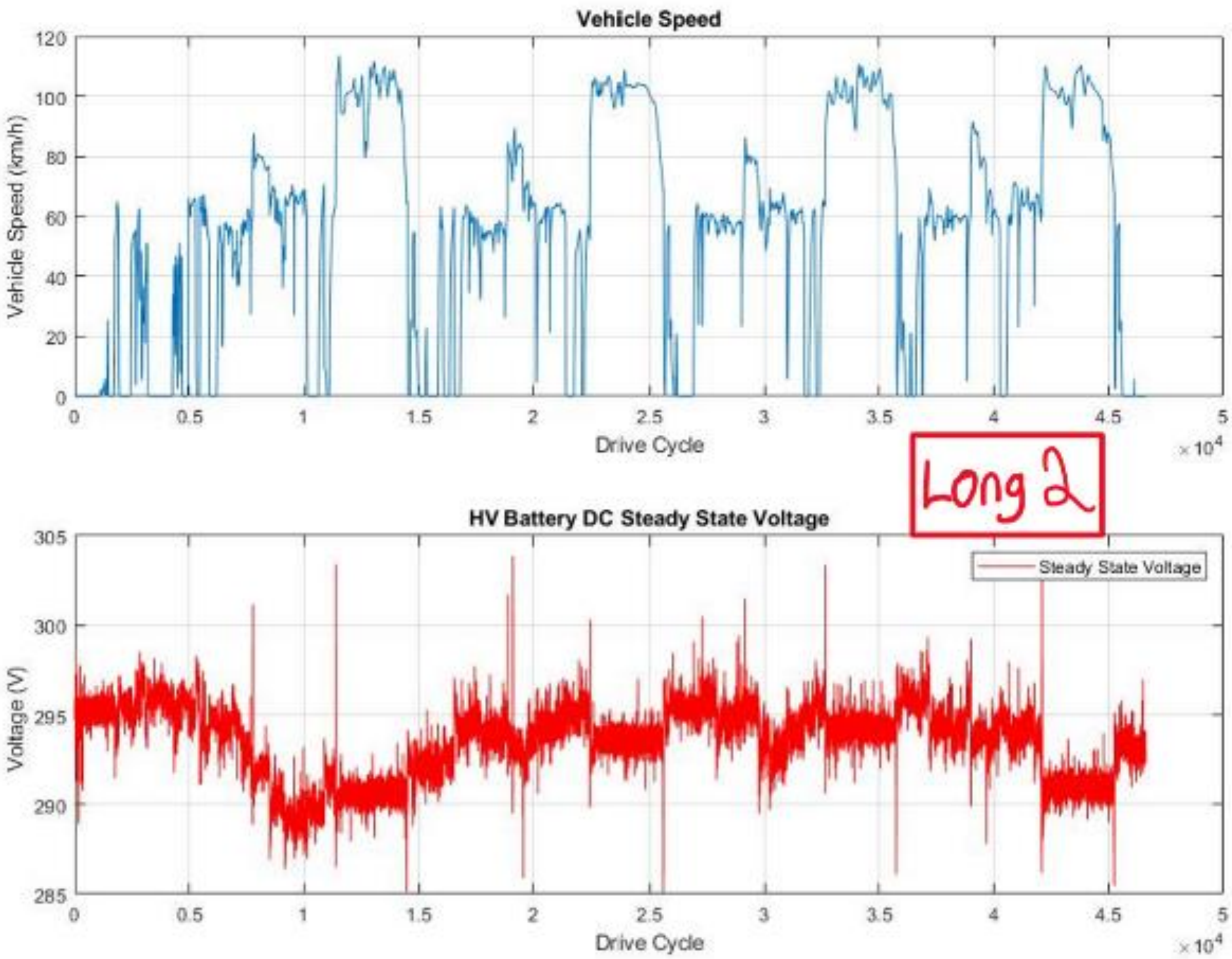

Figure 66: Last 4 McMaster drive cycles and the change in Steady state voltage

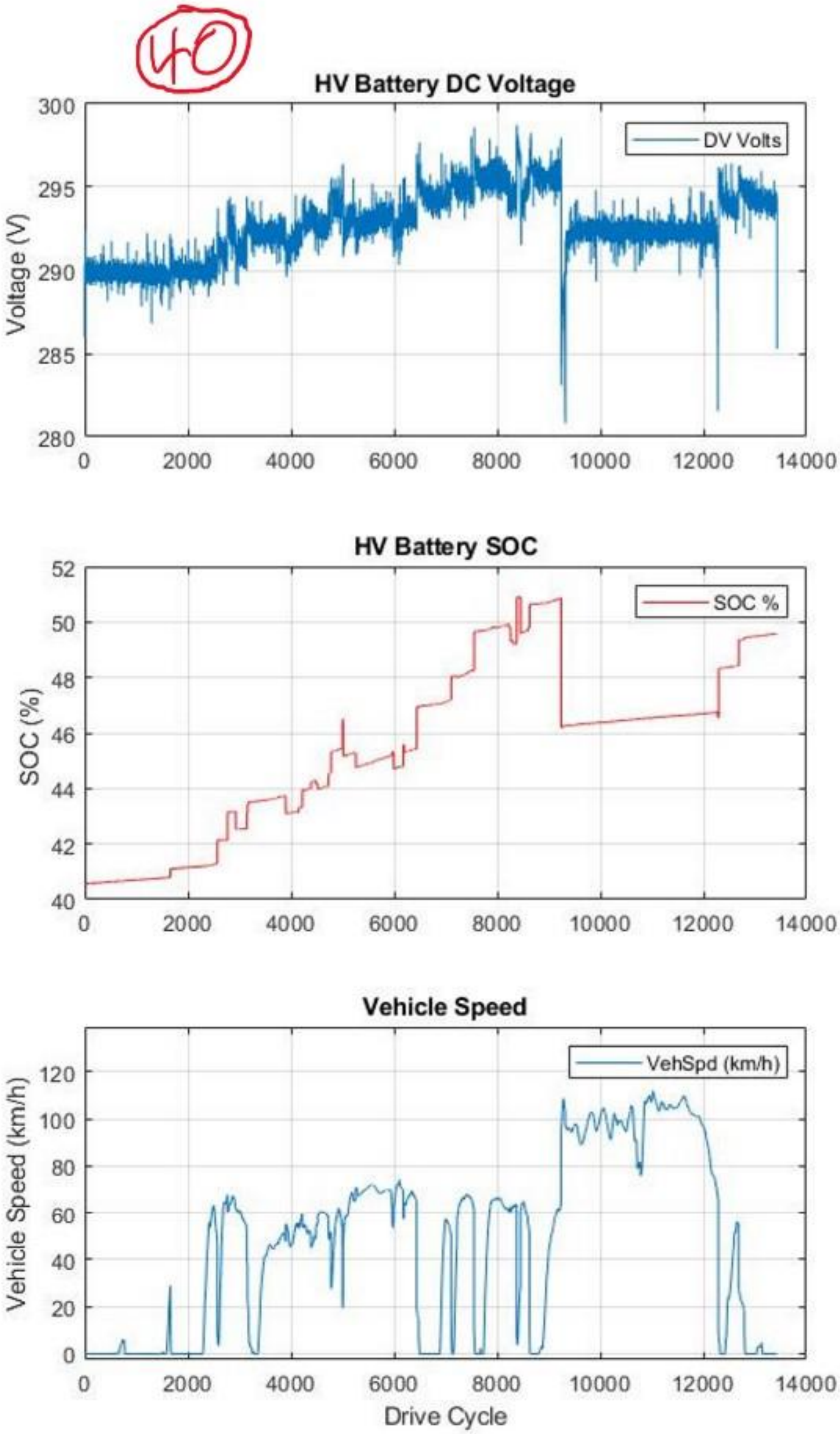

Figure 67: Steady State Voltage Proportional to SOC, Charge Cycle

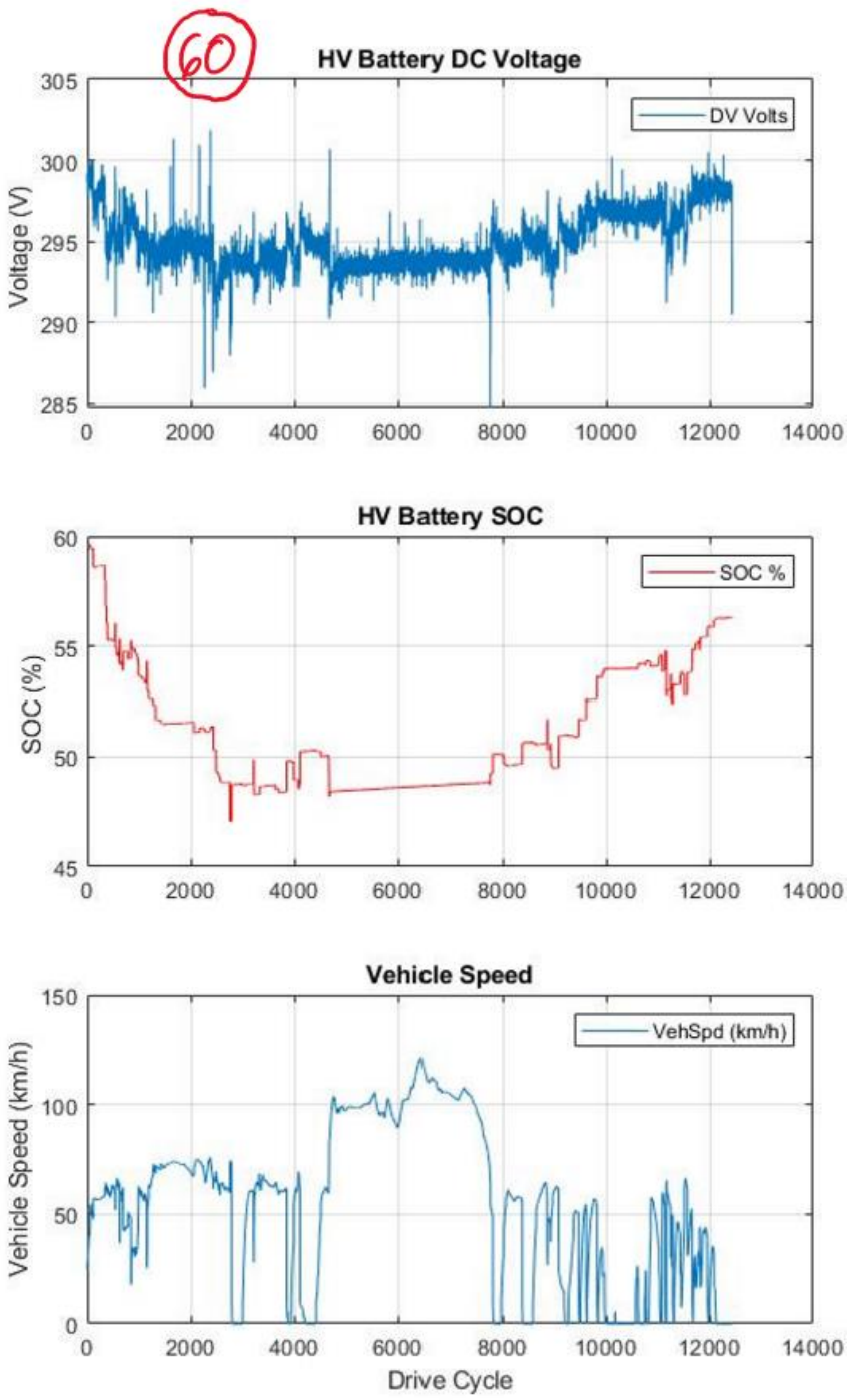

Figure 68: Steady State Voltage proportional to SOC, Discharge Cycle

5.1.4 Long Engine Only

The long engine only cycle was used to set an engine only base line to compare the hybrid improvements of the vehicle. This cycle also was used to confirm the accuracy of the fuel efficacy calculation. The fuel tank was weighed before and after this drive cycle to establish confidence in the fuel efficiency calculation done based on CAN data. Over the course the engine only drive cycle the fuel tank lost 25lbs of fuel or 4.11 gallons of fuel. Resulting in a fuel efficiency of 17.8 miles per gallon. The CAN data calculated 4.02 gallons used over the cycle, resulting in a fuel efficiency of 18.2 miles per gallon. Figure 69 shows the 6 McMaster drive cycles performed during the engine only drive cycle.

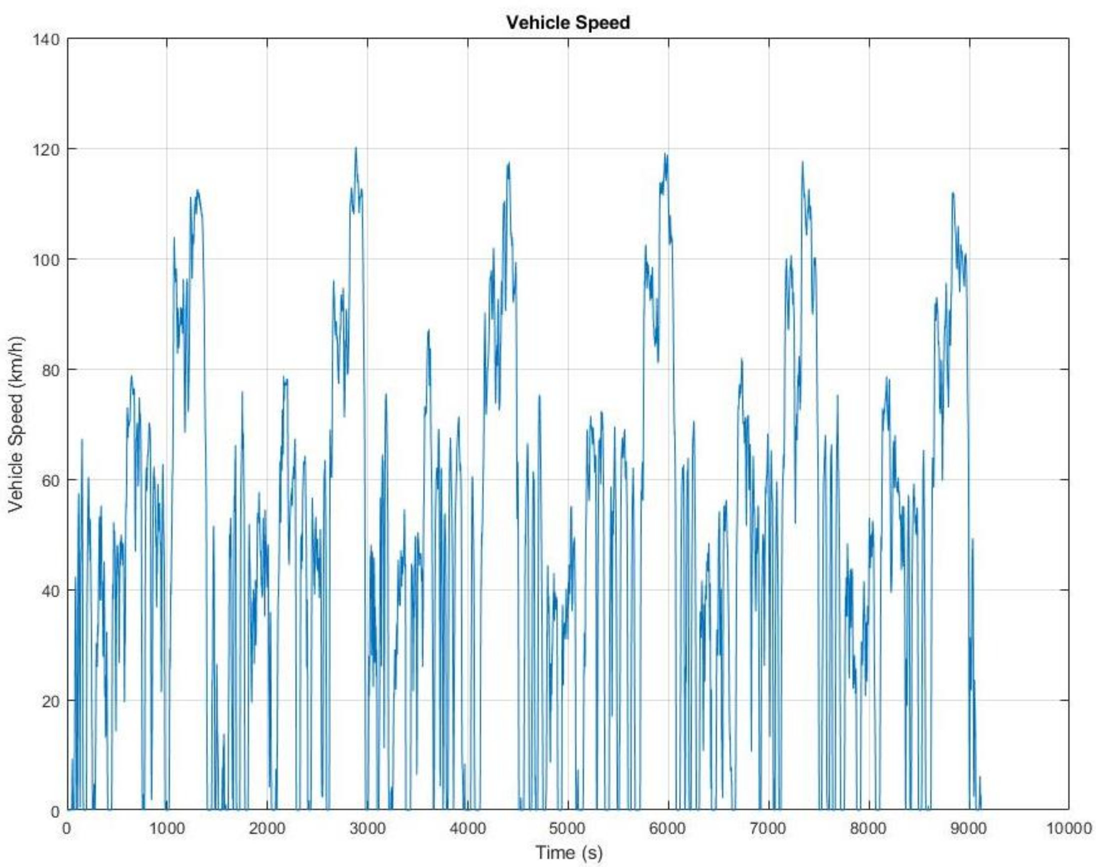

Figure 69: Engine Only Drive Cycle, 6 McMaster Drive Cycles

5.2 HV Charge Sustaining

A non-plug-in hybrid electric vehicle requires a charge sustaining torque strategy that effectively maintains the SOC of the battery within a specified range. The MAC Team charge sustaining functionality was explained in depth in section 4.1.2 and 4.2.2. The MAC Team charge sustaining strategy does not put hard limits on the SOC range but rather uses a target SOC to balance around throughout a drive cycle. The MAC Team target SOC is 50%. Figure 70 shows the motor output torque during the 40% SOC charge cycle. The positive motor torque output is greatly reduced when compared to Figure 71 of the 60% SOC discharge cycle. The reduced positive torque output of Figure 70 is the only way for the battery to gain net energy. The regenerative braking allocation does not change based of SOC, it remains constant due to drivability concerns. Figures 70 & 71 show the adaptation of the charge sustaining strategy, when the SOC is above and below 50%. Figures 65 and 66 show the charge sustaining strategy which maintained the battery SOC for 9 McMaster drive cycles for a total of 183 km.

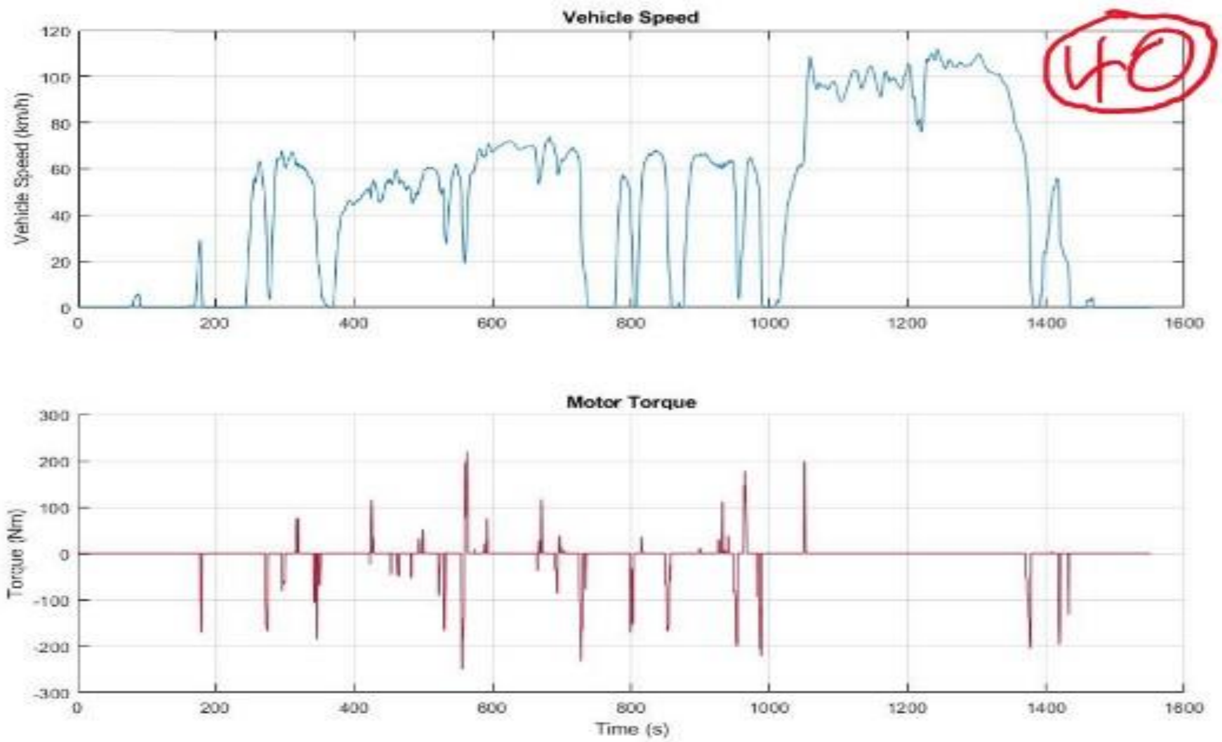

Figure 70: 40% SOC Charge Cycle Motor Torque Output

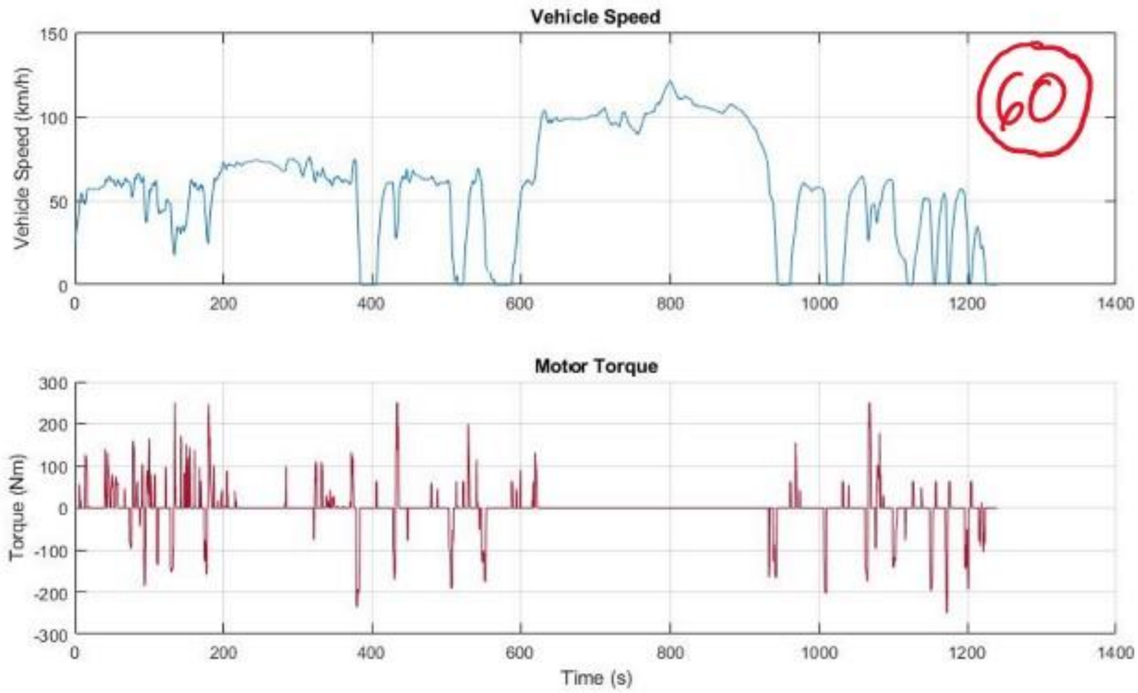

Figure 71: 60% SOC Discharge Cycle Motor Torque Output

5.3 Fuel Efficiency

The MAC Team Vehicle has varying fuel efficiency based on vehicle state Table 1 shows the varying fuel efficiency between the performance evaluation drive cycles.

Drive Cycle	Fuel Efficiency (MPG)
40% Charge Cycle	18.6
60% Discharge Cycle	19.4
Long Hybrid Cycle	19.2
Long Engine Only Cycle	18.2

Table 1: Performance Evaluation Drive Cycle Fuel Efficiency

The long hybrid cycle has a fuel efficiency of 19.2 miles per gallon an increase of 5.5% over the long engine only cycle of 18.2 miles per gallon. Figure 72 shows all the operating points of the engine throughout the engine only drive cycle. The red line enclosing the points represents the maximum engine torque curve, and the green line represents the engine optimal efficiency line. The MAC Team control strategy attempts to operate the engine around the OEL, according to section 4.1.1. Figure 73 shows the engine operating points during the first section of the long hybrid cycle. The red markers represent the engine operating points during motor operation. The circle seen in Figure 73 displays an absence in engine operating points when compared to the engine only engine operating points graph. This gap in engine operating points can also be seen in Figure 74 the second section of the long hybrid cycle. The red Engine Operating Points (EOP) seen in Figures 73 & 74 largely fall above the green optimal efficiency line and many more engine operating points fall along the maximum engine torque curve during hybrid operation when compared to the engine only operation. According to section 4.1.1 and 4.2.1, the separation between the engine output torque and the desired engine OEL can be attributed to the charge sustaining algorithm. Figures 75 & 76 show the engine operating points during the 40% charge cycle and the 60% discharge cycle. Figure 75 shows the limited motor activity during a charge heavy cycle. Figure 75 shows the gap between the OEL and the EOP but also displays the EOP following a similar shape to the OEL as the engine speed increases. The gap between the EOP and the engine OEL is also seen in Figure 76 during the discharge cycle. This should lead to more EOP along or close to the OEL. Figures 77 & 78 show in blue the engine torque request being sent to the engine during the operation of the motor. Theses requests match up with the engine output seen in red and are often outside the engine maximum available torque in both figures. These larger requests were not observed during MIL testing and is likely the reason for only a 5.5% fuel efficiency improvement.

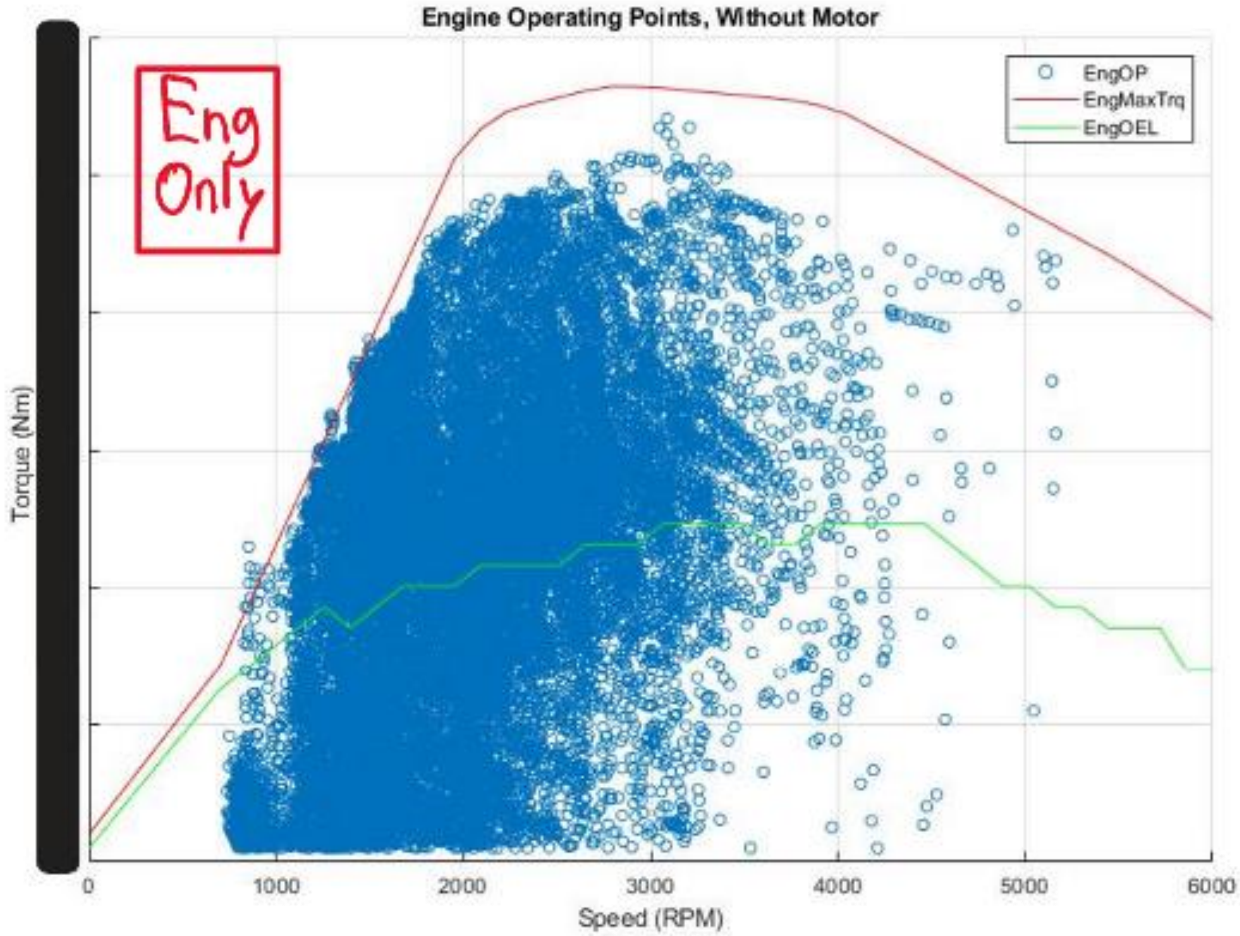

Figure 72: Engine Only Operating Points

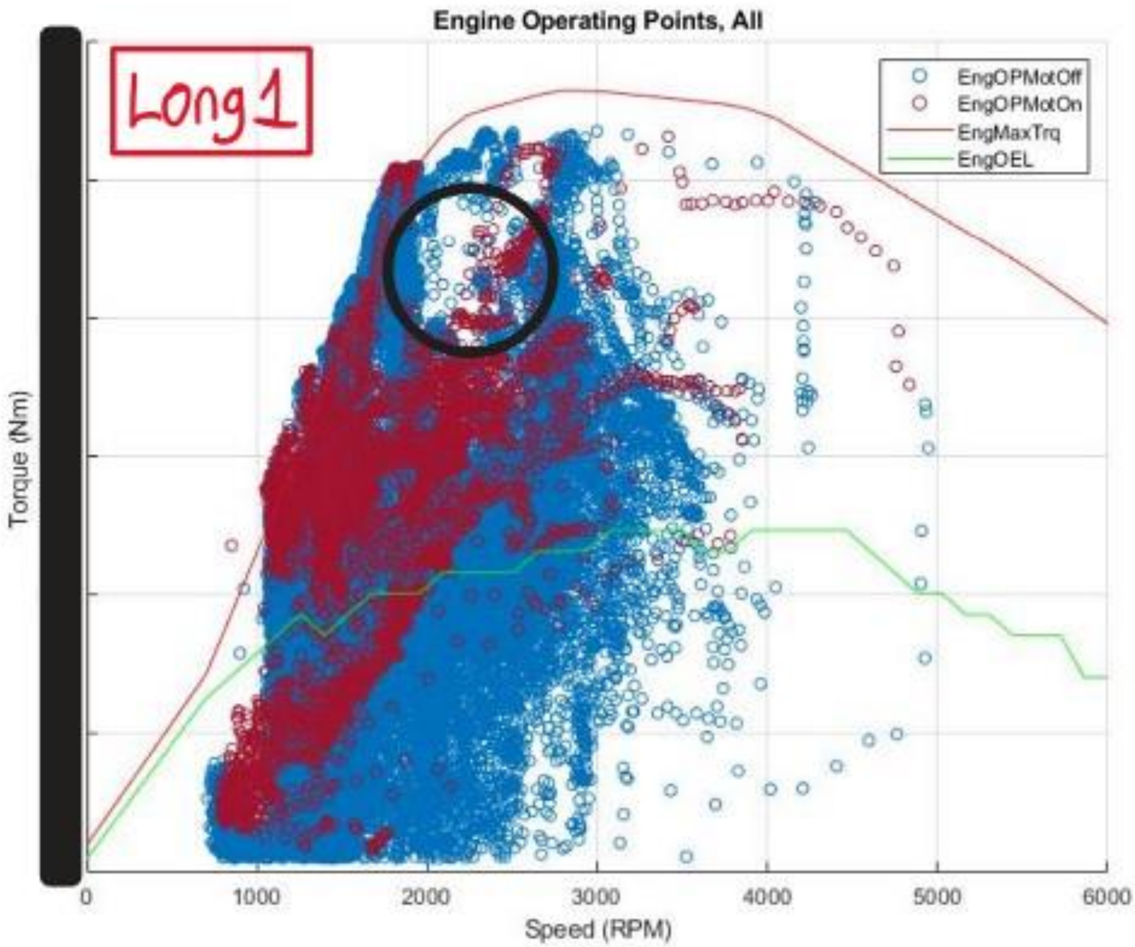

Figure 73: Engine operating points during the first 5 McMaster drive cycles of the long hybrid cycle.

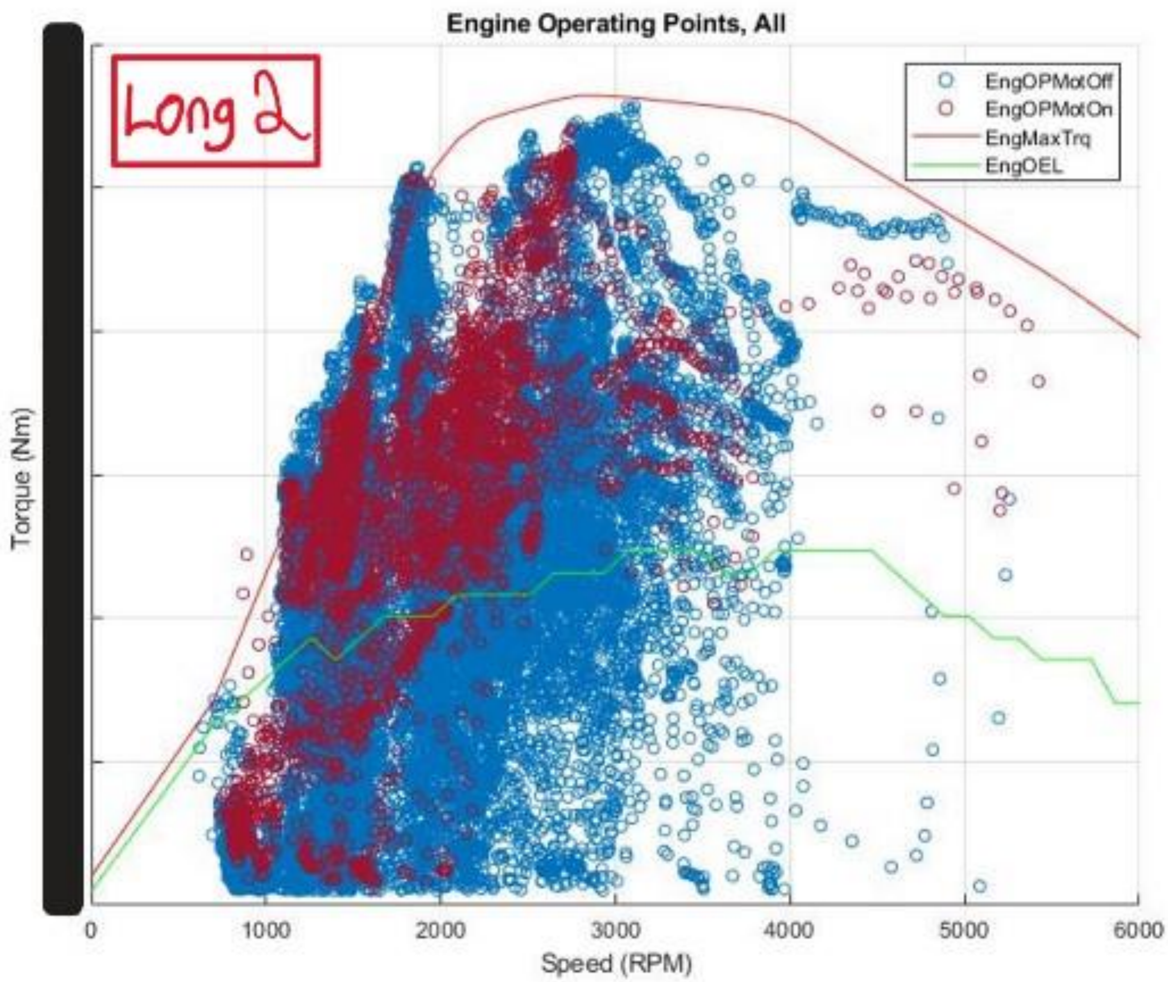

Figure 74: Engine operating points during the last 4 McMaster drive cycles of the long hybrid cycle.

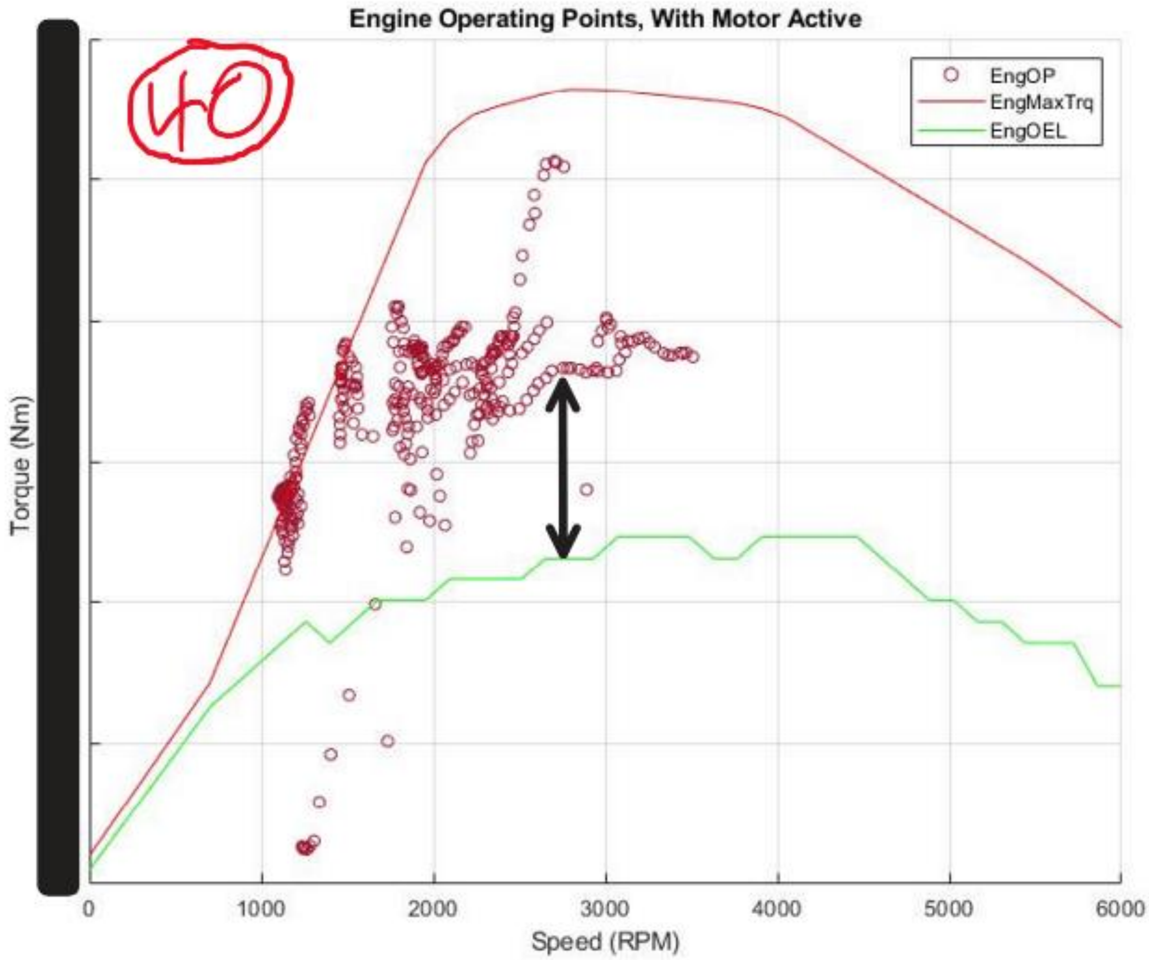

Figure 75: Engine Operating Points during Motor Output of 40% Charge Cycle

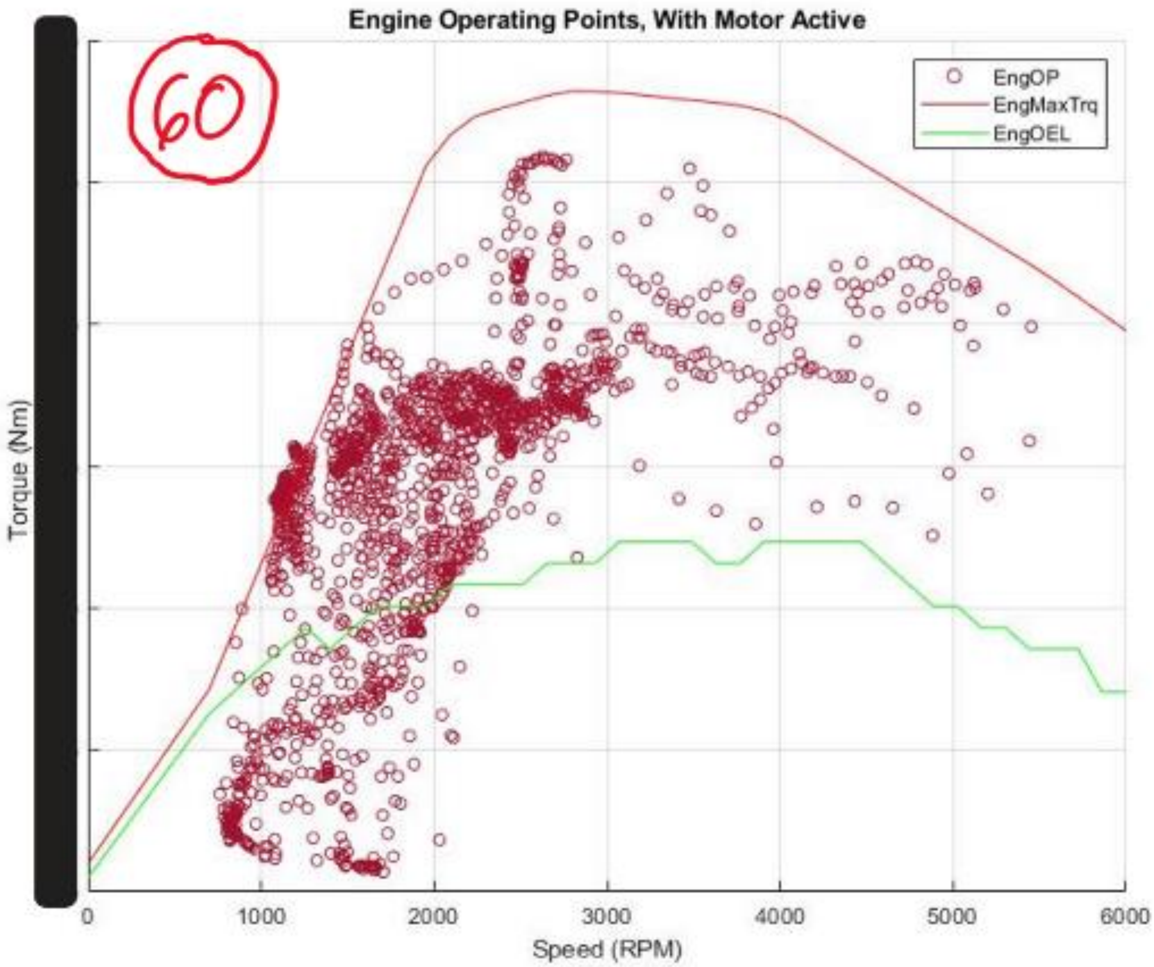

Figure 76: Engine Operating Points during Motor Output of 60% Discharge Cycle

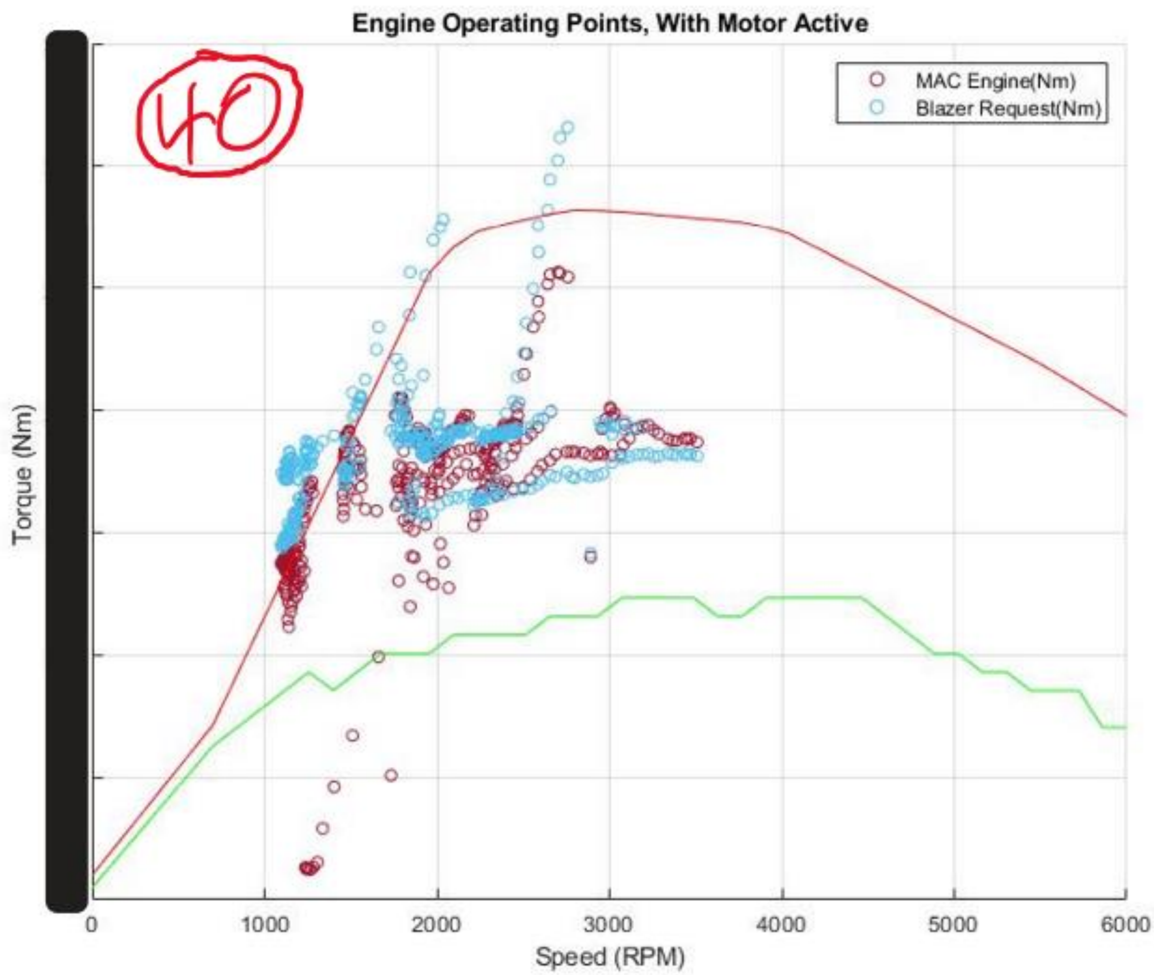

Figure 77: Engine Output Request Points in Blue, Engine Output Points in Red, during Motor Output of 40% Charge Cycle

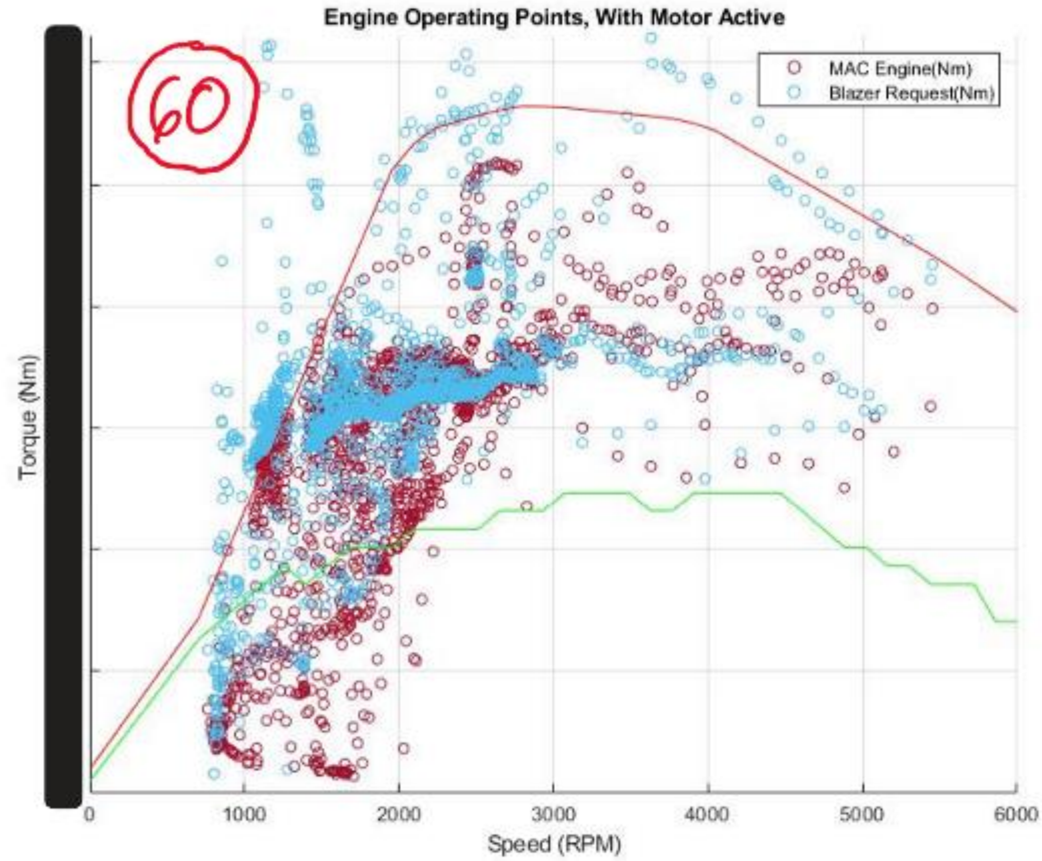

Figure 78: Engine Output Request Points in Blue, Engine Output Points in Red, during Motor Output of 60% Discharge Cycle

5.4 Driveability

Driveability is a relatively subjective metric when evaluating a vehicle, it encompasses several aspects of vehicle behaviour, including smooth acceleration and operation, reliable and consistent braking and the vehicles responsiveness.

5.4.1 Acceleration

To receive a positive driveability metric the acceleration of the vehicle must be smooth and responsive to the driver's inputs. The engine torque request is larger than the OEL for most of the vehicle's operation, but this did not lead to noticeable driveability discomfort from the driver. Accelerations from the MAC Team vehicle was a relatively smooth experience. Figure 80 shows a section of the 60% discharge cycle with 3 acceleration events. The responsiveness of the motor and engine output torque correlate with the increase in accelerator pedal position, demonstrating good responsiveness. The relative smoothness of the vehicle speed curve and torque output curve lead to the smooth acceleration claim from the subjective driver experience.

A standard metric used to evaluate a vehicles ability to accelerate is a 0-100km/h test. Figure 81 displays a 0-100km/h test the MAC Team vehicle performed. The MAC Team Vehicle has a 0-100km/h time of 13 seconds, Figure 81 shows the engine and motor torque output to achieve this time and the corresponding voltage drop of the HV battery due to the motor's torque output. A 13 second 0-100km/h is very slow compared to other vehicles. The maximum continuous torque output of the YASA Motor is 250Nm. During the 0-100 test the YASA operates at its maximum torque for only a moment due to the rapid drop in voltage from the HV battery. In order to avoid an under voltage fault triggered by the Rinhart motor controller the YASA torque output must be held back. This is a factor contributing to reduce the MAC vehicle's ability to accelerate at a higher rate. Another contributing factor can be found in Figure 79 that shows the engine operating points during the 0-100 test. The engine is not operating near to its maximum torque output line in red. The engine does operate along its maximum torque output line during regular operation seen in Figure 76, 77 & 78.

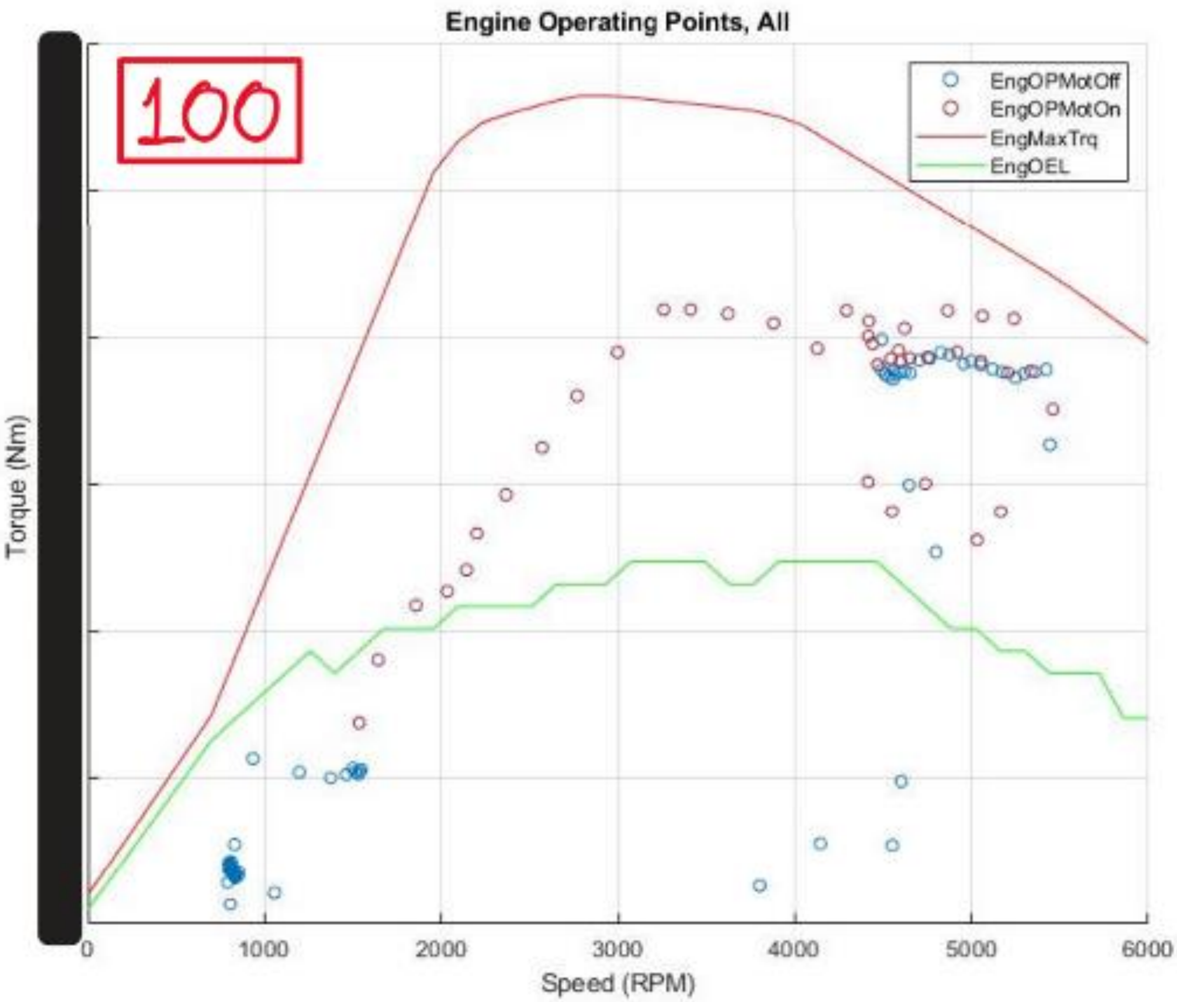

Figure 79: Engine Operating points during 0-100 test. Red points represent engine operating while the motor is outputting torque. Blue points represent the engine operating by itself.

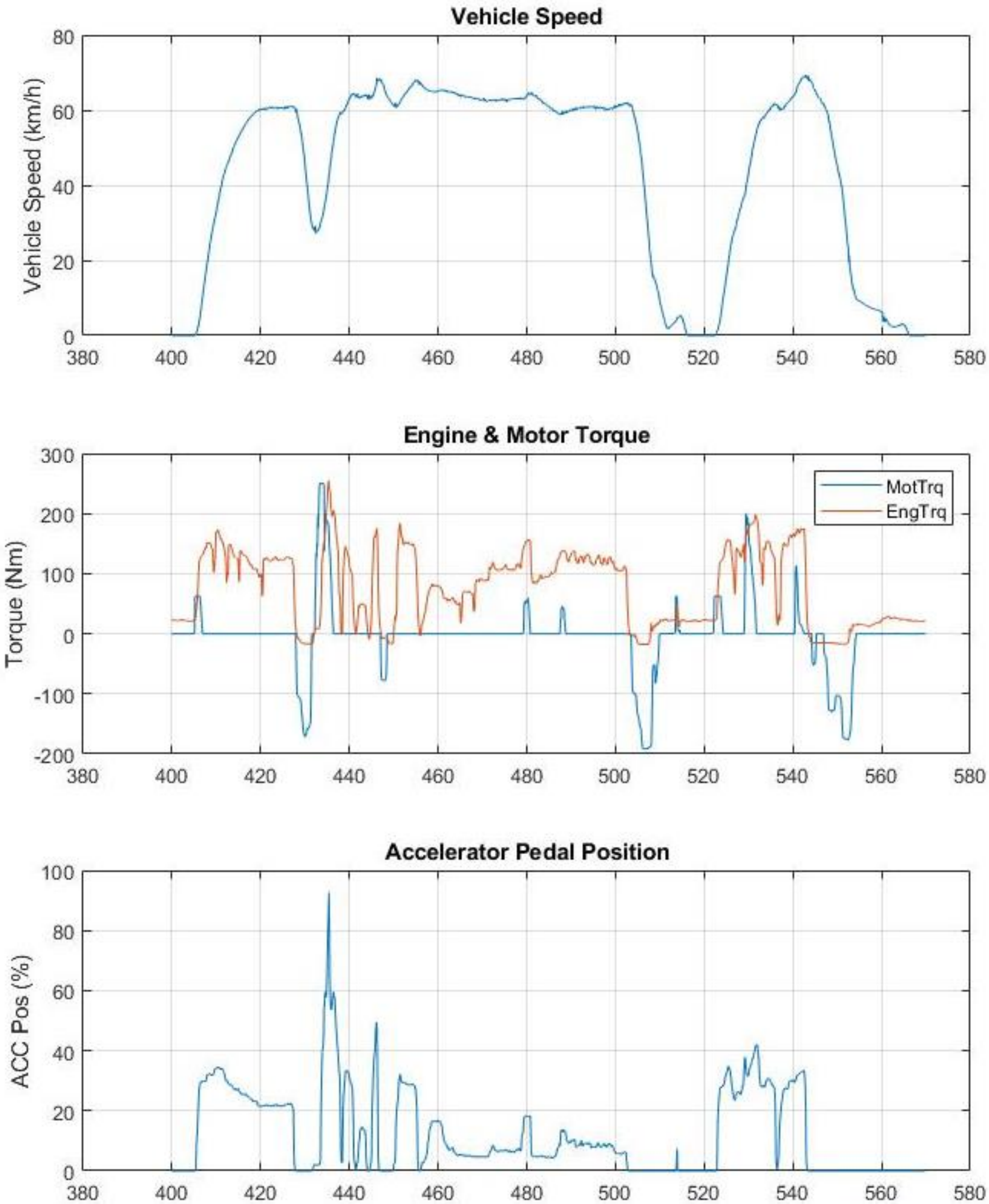

Figure 80: Acceleration Events during 60% Discharge Cycle

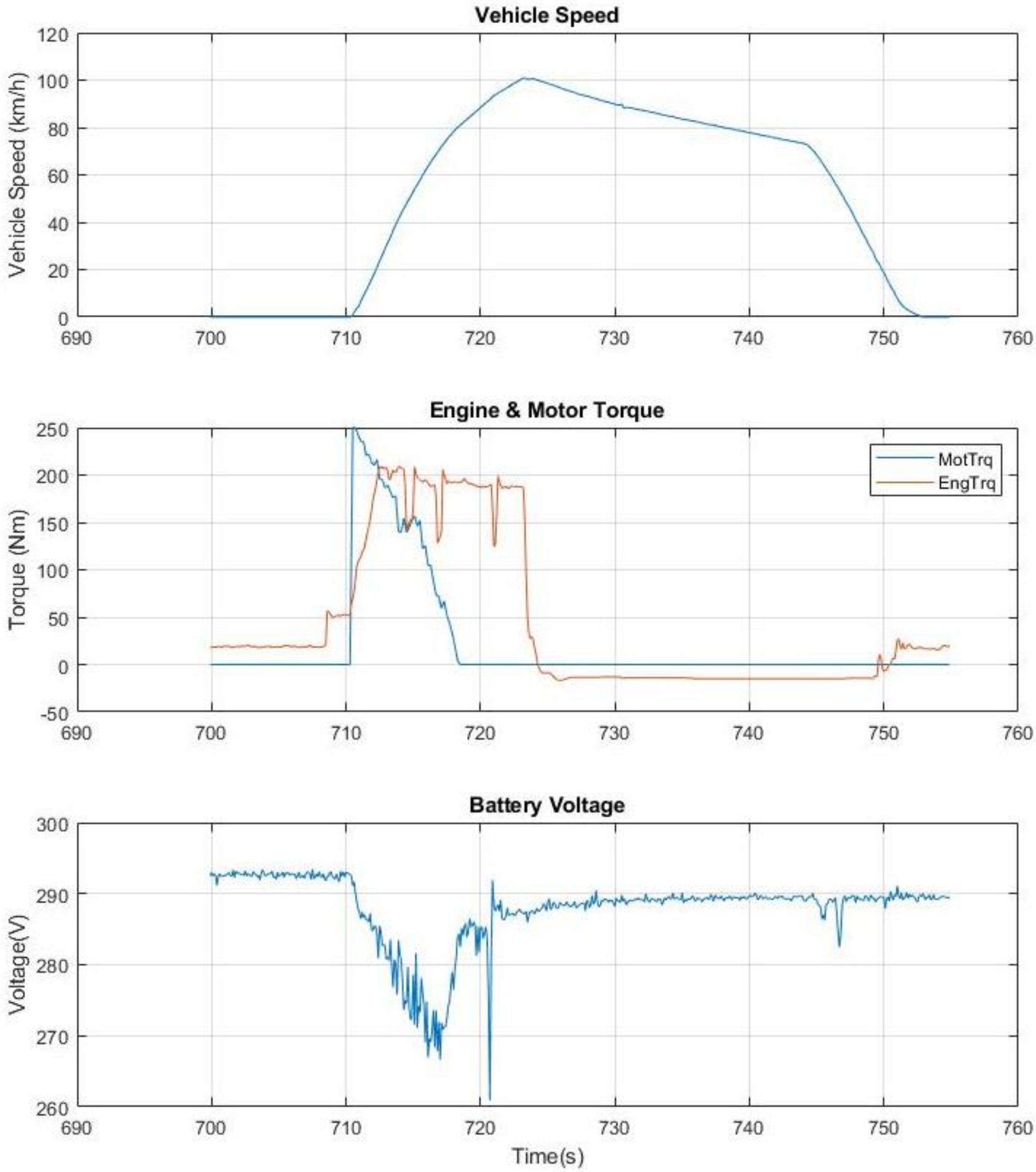

Figure 81: 0-100km/h Acceleration Test

5.4.2 Regenerative Braking

The regenerative braking must be reliable and predictable for the driver, the MAC Team vehicle's regenerative braking was proportional to the brake pedal position leading to predictable braking profiles. Figure 82 shows that the motor regenerative torque is directly proportional to brake pedal position.

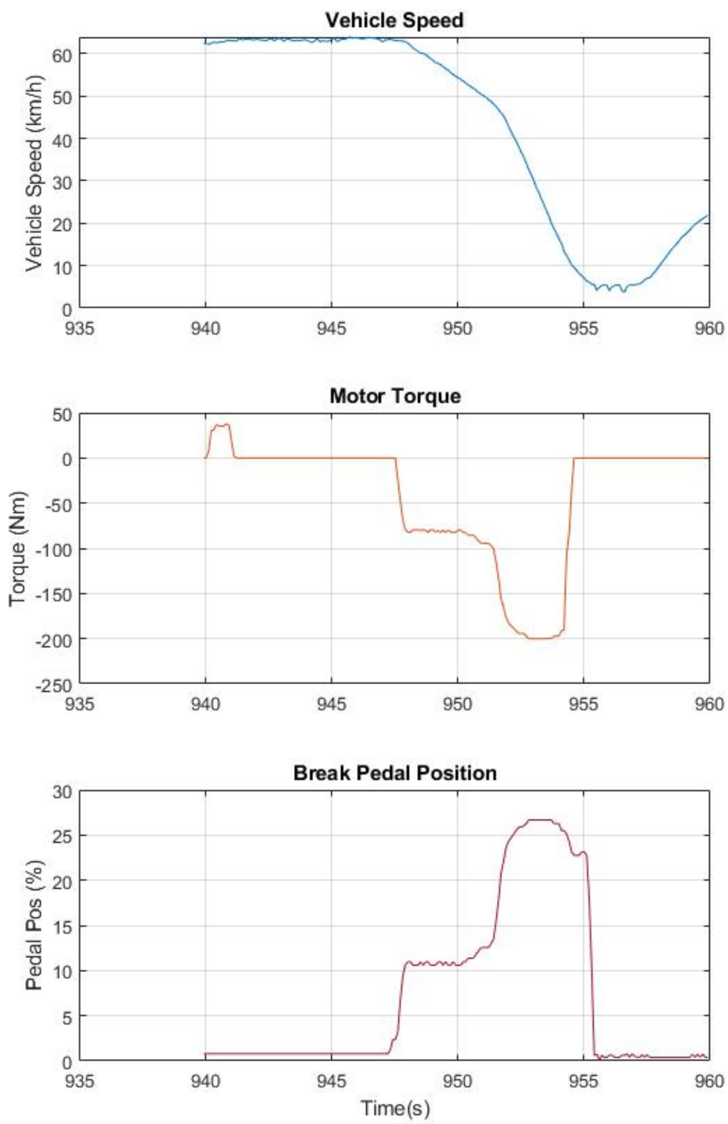

Figure 82: Braking event During 40% Charge Cycle

5.4.3 Clutch Speed Matching

The clutch speed matching algorithm is discussed in section 3.4.8, and it was developed with drivability in mind. The clutch opens when the MAC Team vehicle reaches 80km/h and closes again when the vehicle speed slows to 70km/h. The driver will be aware when the clutch opens and closes at speed. Figure 83 shows the clutch opening when the vehicle reaches 80 km/h. For a few seconds before the clutch opens the motor is not outputting any torque, when the clutch opens the driver will notice the missing resistance of the motor free wheeling due to the open clutch. Figure 84 shows the clutch closing as the MAC Team vehicle decelerates to 70km/h. When the clutch closes the motor speed drops roughly 100 RPM and this difference in speed can be felt by the driver.

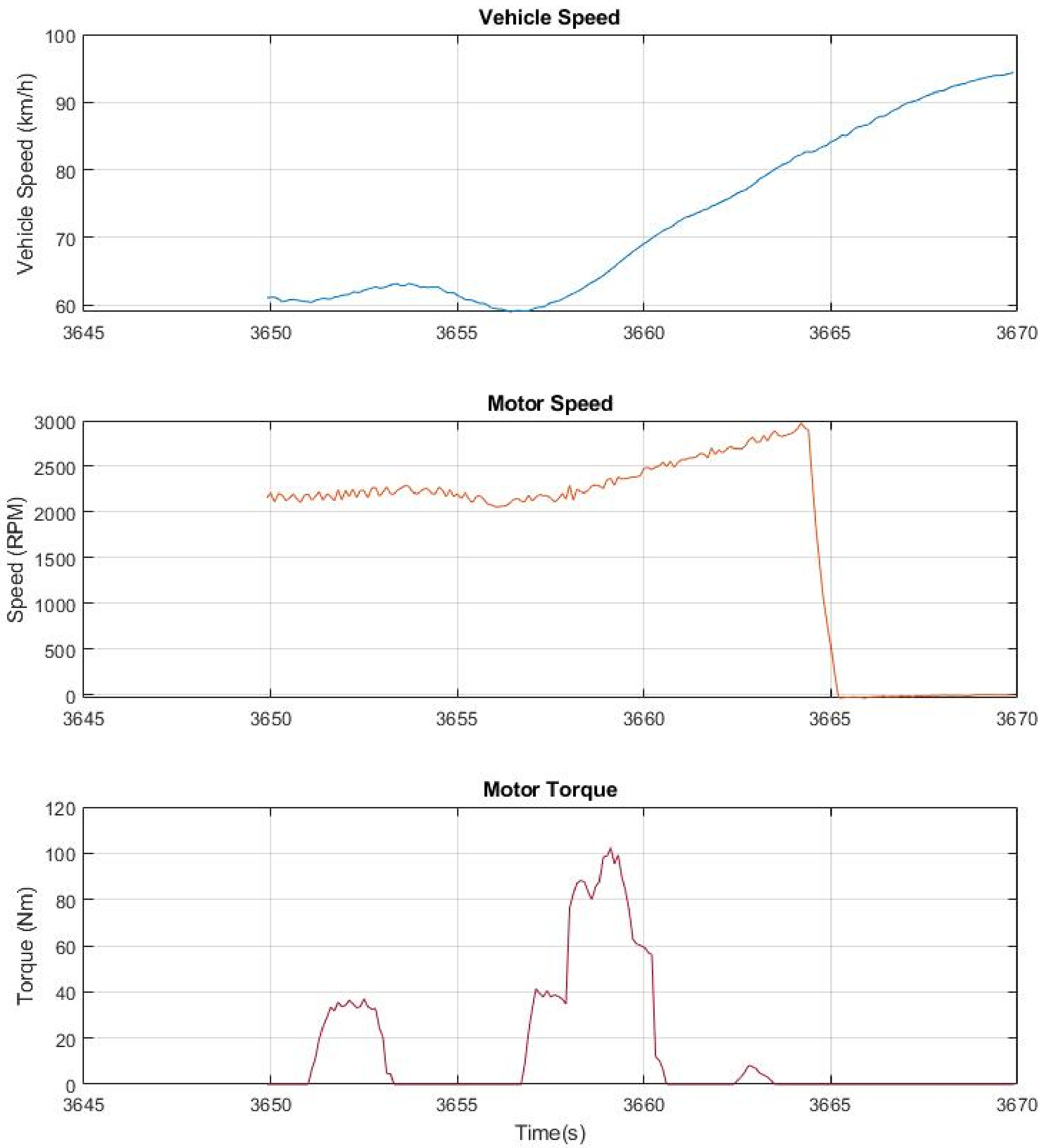

Figure 83: Clutch Opening at 80km/h

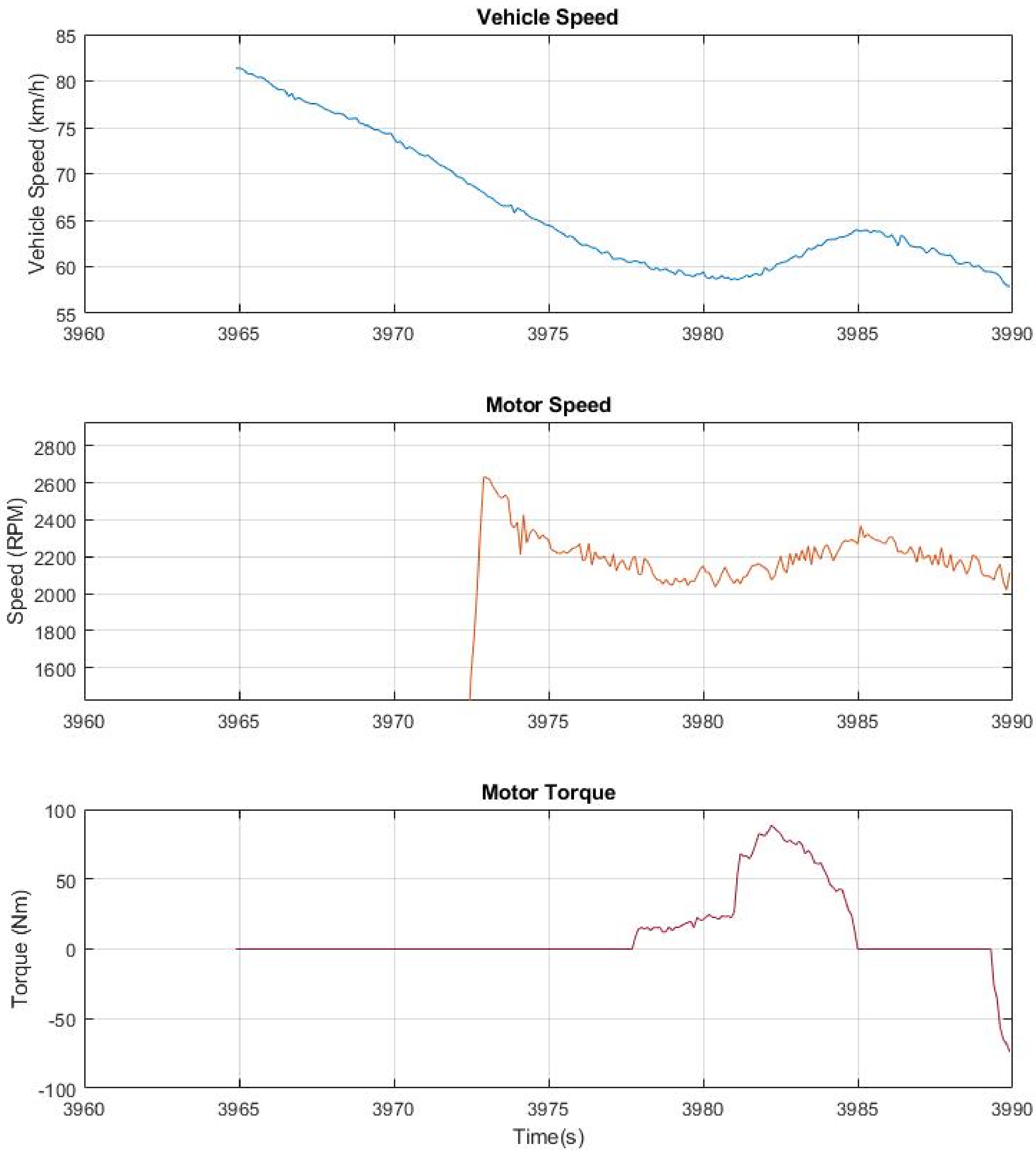

Figure 84: Clutch Closing at 70km/h

5.5 Summary

The MAC Team vehicle's performance was evaluated over 4 different drive cycles. A Charge heavy McMaster drive cycle, a discharge heavy McMaster drive cycle, a long hybrid drive cycle consisting of 9 consecutive McMaster drive cycles and a long engine only drive cycle consisting of 6 consecutive McMaster drive cycles. The 3 metrics being evaluated for the MAC Team vehicle are its charge sustaining capability, fuel efficiency, and driveability. The MAC Team vehicle is capable of maintaining charge sustaining over the long hybrid drive cycle confirming the MAC Team vehicle has charge sustaining ability. The fuel efficiency of the MAC Team vehicle is 19.2 miles per gallon, based on the long hybrid drive cycle. The fuel efficiency is an increase of 5.5% over the engine only operation but falls well short of matching the stock 2019 Chevrolet Blazer fuel efficiency. Based on the engine operating points seen during hybrid drive cycles future work could increase the overall fuel efficiency of the vehicle. The last metric of drivability is a more subjective metric but over all the driveability of the MAC Team vehicle is very high. The only driveability issue is the clutch opening and closing operation, which has been mitigated through testing.

Chapter 6

Conclusions and Future Work

6.1 Thesis Summary

This thesis begins with a brief explanation of trends in the automotive industry and an overview of the EcoCAR Mobility Challenge. The EcoCAR Mobility Challenge is the driving force behind the control strategy development and implementation discussed in this thesis. Chapter 2 provides an overview of model-based design through Model-in-the-Loop and describes the vehicle model developed for control strategy simulation. Chapter 3 explains the importance of component testing prior to integration into the MAC Team vehicle, aiding in the development of control loops for a variety of components. Chapter 4 delves into the full vehicle control system, discussing the energy management module that is responsible for the torque split and charge sustaining algorithms. Chapter 5 demonstrates the MAC Team vehicles ability to operate in real-world conditions accumulating over 1500km of on-road hybrid driving.

6.2 Future Work

A deeper investigation into the engine operating points is required if an increase in fuel efficiency of the MAC Team vehicle's is desired. Figures 77 and 78 show the engine operating points in red and the engine request in blue. An analysis of the wheel torque command coming from the pedal map should be performed. If the issue is that the driver request is simply too large for the 1.5L MAC Team engine to operate along its optimal efficiency line consistently with the current components in place. A new plug-in battery could be used to operate the YASA motor more often and the YASA's torque output will not be hindered by the charge sustaining requirement if a plug in HV battery in installed.

The 0-100km/h test has clear errors in the control strategy output, the engine does not operate at its peak torque output for any of the 0-100km/h test. This requires an investigation into the engine torque request for this functionality but also adding a plug-in HV battery could allow the MAC Team vehicle to rely on the YASA more during this operation. The YASA only operates at it maximum output torque for an instant during this test.

6.3 Conclusion

The increasing demand for sustainable transportation solutions has led to the rapid evolution of hybrid and electric vehicle. This thesis, undertaken as part of the EcoCAR Mobility Challenge, presents the development and implementation of a control system for a P4 parallel through-the-road hybrid electric vehicle. A comprehensive vehicle model was developed using MATLAB Simulink. This model was used to model overall vehicle performance and component specific performance through out the EcoCAR Mobility Challenge and served as the foundation for the subsequent stages of control system development. Extensive component and vehicle testing formed the crux of this thesis. Bench tests for the YASA P400 electric motor, high voltage battery pack and for the belted alternator-starter. These bench tests provide invaluable data that aided in the implementation of the component control loops into the MAC Team vehicle. On-road vehicle testing further refined the drivability of the MAC Team vehicle, the charge sustaining of the high voltage battery, and the energy management strategy, emphasizing efficient torque split between the engine and electric motor. The full vehicle control system with its 10 control modules, that successfully operated the MAC Team vehicle for over 1500km on public roads stands as a testament to the rigorous testing and adherence to the development process. The control systems adaptability and efficiency are evident in its performance during real-world testing scenarios. This thesis not only contributes to the academic understanding of hybrid vehicle control strategies but also has practical implications for the automotive industry. The methodologies and findings can guide future projects aiming to optimize hybrid vehicle performance. As the world moves towards greener transportation solutions, the insights from this thesis will undoubtedly play a pivotal role in shaping the next generation of hybrid vehicles.

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