Development of a Control System for a P4 Parallel-Through-The-Road Hybrid Electric Vehicle

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BY

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Lay Abstract

During the re-engineering of a Hybrid Electric Vehicle different expectations must be considered, for example set government fuel economy regulations, defined performance targets, novelty in innovation, stakeholder expectations as well as the used vehicle platform and the available components. The re-engineering process will be done according to the vehicle development process of the EcoCAR Mobility Challenge. Summarized expectations are the use of this vehicle inside a car-sharing service for the Greater Toronto Hamilton Area targeting "Millennials" while focusing on fuel economy improvements and a low cost of ownership.

The research shown in this thesis is set by the requirements derived from the expectations mentioned above. One point of interest is achieving a working control system able to operate close to an optimal state to maximize fuel efficiency and ensuring stock vehicle performance targets. Therefore, the control system has to use the electrification components in an intelligent way. Defining what intelligent control of the engine and the electrification components was one of the main challenges.

This thesis outlines how developing a control system for a Hybrid Electric Vehicle can be realized while ensuring that all included interests are met. The object of this research contains choosing the necessary controllers, building a sufficient vehicle simulation model, developing the energy management algorithm, validating the model performance and evaluating the gathered results.

Abstract

This thesis outlines the development of a control system for a P4-P0 Parallel-Through-The-Road Hybrid Electric Vehicle. This project was part of the EcoCAR Mobility Challenge, an Advanced Vehicle Technology Competition, sponsored by the U.S. Department of Energy, MathWorks and General Motors. The McMaster Engineering EcoCAR team is participating in its second iteration, re-engineering a 2019 Chevrolet Blazer to suit a car-sharing service located within the Greater Toronto Hamilton Area. The proposed architecture uses a 1.5L Engine together with a Belted Alternator Starter motor connected to the traditional low voltage system. The rear axle is electrified containing an Electric Machine, a power oriented Battery Pack and team-designed gear reduction as well as a clutch. The whole rear powertrain is operating at high voltage and has no connection to the traditional low voltage system. Fuel economy improvements up to 12% can be expected while maintaining stock performance targets.

A vehicle simulation model was built to accompany the vehicle design process. This includes a mathematical representation of all powertrain components, the development of energy management algorithms, the design of the Hybrid Supervisory Controller structure, and validating and discussing gathered results. Furthermore, all necessary controllers were chosen and communication within them was established by designing the serial data architecture.

The developed energy management algorithm is customized to utilize the strengths of all components and this specific architecture. A simple rule-based algorithm is used to operate the engine as close as possible to its most fuel efficient operation point at any time. The P4 and P0 motor are used to apply supportive torque to the engine or load the engine with a negative torque. In that way the energy can be regenerated inside the powertrain and charge sustaining operation

can be achieved. Fuel economy and performance targets are used to discuss the assumed performance of the vehicle once re-engineered. The set targets range from city and highway fuel economy to IVM – 60 mph acceleration time.

Overall the developed control system suits a car-sharing service with its ability to adapt to the occurring driving situations ensuring a close to optimal operation for any known or unknown driving situation. It focuses on modularity, simplicity and functionality to allow a working implementation in future years of the EcoCAR Mobility Challenge.

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Notations and Abbreviations

ACC .... *Adaptive Cruise Control*

ANL .... *Argonne National Laboratory*

AVTC .... *Advanced Vehicle Technology Competition*

BAS .... *Belted Alternator Starter*

BCM .... *Body Control Module*

BEV .... *Battery Electric Vehicle*

BSM .... *Battery System Manager*

CAFE .... *Corporate Average Fuel Economy*

CAN .... *Controller Area Network*

CAVS .... *Connected Automated Vehicle System*

CD .... *Charge Depleting*

CS .... *Charge Sustaining*

CSMS .... *Control System, Modeling and Simulation*

DOE .... *Department of Energy*

DOF .... *Degree of Freedom*

DP .... *Dynamic Programming, Dynamic Programming*

EBCM .... *Electronic Brake Control Module*

ECM .... *Engine Control Module*

ECMS .... *Equivalent Consumption Minimization Strategy*

ECU .... *Electronic Control Unit, Electronic Control Unit*

EM .... *Electric Machine*

EMC .... *EcoCAR Mobility Challenge*

EMS .... *Energy Management Strategy*

ESS .... *Energy Storage System*

FCM .... *Rear Control Module*

GA .... *Genetic Algorithm*

GHG .... *Greenhouse Gas*

GM .... *General Motors*

GTHA .... *Greater Toronto Hamilton Area*

HEV .... *Hyrbid Electric Vehicle*

HIL .... *Hardware-in-the-Loop*

HPCM .... *Hybrid Powertrain Control Module*

HV .... *High Voltage*

I/O .... *Input and Output*

ICE .... *Interal Combustion Engine*

LKA .... *Lane Keeping Assist*

LUT .... *Look-up Table*

LV .... *Low Voltage*

MaaS .... *Mobility-as-a-Service*

MbD .... *Model-based Design*

MCM .... *Motor Control Module*

MIL .... *Model-in-the-loop*

OOL .... *Optimal Operation Line*

PFMEA .... *Process Failure Mode and Effect Analysis*

PropSys .... *Propulsion System*

PSCM .... *Power Steering Control Module*

RB .... *Rule Based*

RCM .... *Rear Control Module*

RMSE .... *Root-Mean-Square Error*

RPN .... *Risk Priority Number*

SAE .... *Society of Automotive Engineers*

SIL .... *Software-in-the-Loop*

SOC .... *State-of-Charge*

SUV .... *Sport Utilitiy Vehicle*

TCM .... *Transmission Control Module*

TJC .... *Traffic Jam Chauffeur*

US .... *United States*

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1 Introduction

1.1 Automotive Trends

In agreement with thirteen large automakers, the Barack Obama administration of the United States (US) government implemented stricter fuel economy regulations. Fuel economy values of up to 54.5 mpg shall be reached for cars and light-duty vehicles by the year 2025 [1]. This resulted in the Corporate Average Fuel Economy (CAFÉ) regulations, which are mandatory for all vehicles sold from the model year 2011 until the model year 2025 [2]. During the 2016 mid-term review it was stated that progress was made for reducing greenhouse gas (GHG) emissions but reaching an average fuel economy of 54.4 mpg was deemed to be unrealistic. This was due to a shift in the customer's wants for trucks and Sport Utility Vehicles (SUVs) [3]. In 2018, the US government passed a bill to stagnate the desired fuel economy to the model year 2021 goals. Those goals are targeting a fuel economy of 37 mpg for vehicles sold between 2021 and 2025 [4]. These changes were justified by the significantly reduced cost on the American consumers to keep future vehicles affordable. In absolute number, the average fuel economy of cars needs to increase from an average of 32.2 mpg, in 2018, to only 37 mpg in 2021 [5]. This will result in an overall fuel economy improvement of around 14% over three years.

Regulations like the CAFE ones are forcing the automotive industry to change vehicle development. Electrification and Hybridization of vehicles is one of the approaches automakers are using to improve fuel economy, which is causing an increased market share for battery electric vehicles (BEVs) and Hybrid Electric Vehicles (HEVs) [6]. Additionally, automakers must fulfill the needs and wants of their customers and the changing social attitude towards different mobility approaches. For example, since September 2017 Crossover Utility Vehicles (CUVs) are overtaking sedan style light-duty vehicles as the largest market share for sold vehicles in the US [7].Next younger generations, such as "Millennials", are pushing the automotive market to change the convention ownership strategies with newly invented Mobility-as-a-Service (MaaS) applications like car-sharing or ride-sharing services. Trends have shown that shared-vehicle or shared-ride services should be highly considered when approaching the future of mobility [8]. In parallel, Connected Automated Vehicle Systems (CAVSs) are helping vehicle designers to improve fuel economy and to achieve zero-crash transportation [9]. The following paragraphs will be used to analyze upcoming trends in automotive development and research areas to a point where a vehicle concept can be defined that fits in the near-future situation of mobility. These paragraphs are aiming to cover different degrees of hybridization, state-of-the-art vehicle types, MaaS applications and a short overview of driving automation technology.

1.2 Degrees of Hybridization

Hybridization describes a process where a vehicle uses two or more fuel types to propel the vehicle. This thesis will focus on HEV applications; utilizing an Internal Combustion Engine (ICE) in combination with one or more Electric Machines (EMs), power electronics and Energy Storage System (ESS), consisting in most cases of a battery pack. The functionality and the positioning of all components define which type of HEV is described and which degree of hybridization is applied. The classification of hybridization is based on functionality and the electrical components used. Classifications range from micro hybrid applications, mild hybrid applications, power (or full) hybrid applications, and plug-in hybrid applications. Starting with micro hybrid applications, a fuel economy improvement of up to 5% can be expected [10]. Its functionality does not vary broadly from a conventional engine driven vehicle, using simple start/stop functionality with the engine, and no propelling will be done by the electrical powertrain. For mild hybrid applications additional functionalities like propulsion assist and regenerative braking capability are expected to be offered. Fuel economy reductions up to 18% can be expected based on the used voltage level of the system. Mild hybrids voltage levels can vary from 12V or 48V systems, up to systems using 300V or more. Lastly to consider are full hybrids and plug-in hybrids, where a fully integrated electric powertrain can be expected to be on the same level of importance as the engine. A difference that needs to be mentioned is that plug-in hybrids are more efficient because of their possibility to recharge from an outside charging station. Fuel economy improvements of up to 80% can be expected [10].

It is obvious that a higher degree of hybridization is directly correlated with the cost of the vehicle [11]. This is mainly due to the increased size of the battery packs inside the vehicles and expensive permanent magnet materials in current EMs. Based on the size of the battery pack, cost of the battery packs can make up to roughly 60% of the electrical powertrain, where as the EM is taking up to 30% of the cost [12].

1.2.1 Cross-Over Utility Vehicles

As stated by the U.S. Energy Information Administration, CUV sales have overtaken sedans in the US market as the most popular vehicle type in every month since September 2017 [13]. The consumer market is changing towards CUVs which has caused automakers to establish new models or re-engineer older models [14]. CUVs are aiming to combine SUV features with car-based engineering while compromising the loss of heavy off-road use [15]. Instead of using a body on frame construction, CUVs have a unified body structure. Mainly aluminum and steel are used where structural safety will be ensured through well-thought design. This results in weight reduction, fuel economy improvements and car-like handling [16]. Additionally, a CUV has a tall interior, high H-point seating and high ground clearance which all can be classified as typical SUV or truck features [7]. The higher driving position contributes to an increased feeling of safety, which is stated to be an important phycological factor when buying a car. This effect is called the "SUV-effect" which leads to more risky driving behavior [17]. Combing all useful characteristics of an SUV and car-like vehicle, CUVs are designed to be used in a city environment while still offering comfortable drivability over highway driving.

1.2.2 Mobility-as-a-Service

A trend towards individualized lifestyle can be seen in modern western society. This is also reflected in changing mobility requirements where individual needs are getting more attention. Decreasing average salaries and increased urbanization are pushing a need for commuting between cheaper housing in suburban areas and the high-density downtown work areas [18]. An approach to face this upcoming challenge can be seen with MaaS applications, which aim to achieve mobility needs without owning a private vehicle. Further, these applications are targeting to offer better conditions for the customer by offering lower travel cost through external maintenance service and state-of-the-art technology [19]. Car-sharing or ride-sharing services are considered a MaaS application with high future potential. A generation raised with constant access to shared-services is the so-called "Millennials". Accessibility to most of their needs can be done via smartphone. Bike-sharing services, like Social Bicycle Hamilton, can be accessed and paid via smartphone and allow instantly available mobility in a small scale showing financial success [20]. A similar concept is presented by companies like Uber and Lyft. These companies are taking that concept to a higher level incorporating the need for transportation in a taxi-like environment offering ride-sharing [21]. Finally, car-sharing services, like Maven or Car2Go, are gaining more popularity in offering shared-car services for everyday use [22]. Maven, a subsidiary of General Motors (GM), is offering a business plan with a strong connection between automakers, maintenance services and customers, allowing simple access to mobility service from a smartphone [23].

1.2.3 Driving Automation

Driving Automation was outlined by engineering experts according to the Society of Automotive Engineers (SAE) levels. The defined levels start from level 0, including no automation features, and up to level 5, including fully implemented driving automation [24]. Main driving attributes for Driving Automation are safety, fuel efficiency, and comfort. Current state-of-the-art technology is positioned in between level 2 and 3 where the execution of steering, acceleration and deceleration is done by the automated system. Difference between level 2 and 3 can be seen in the ability of the system to monitor driving environment by the human driver in level 2 and the automated system in level 3 [25]. Currently the main implemented features are Park Assist, Adaptive Cruise Control (ACC) and Lane Keeping Assist (LKA). An example for implemented level 3 automation is the Audi AI system including Traffic Jam Chauffeur (TJC) [26].

1.3 EcoCAR Mobility Challenge

Combining future mobility needs and current automotive trends the EcoCAR Mobility Challenge (EMC) incorporates vehicle electrification to achieve set fuel economy targets, the CUV vehicle concept, and MaaS applications under the main goal to achieve a paradigm shift in transportation for future years. The EMC is the latest edition of the Advanced Vehicle Technology Competition

(AVTC) series sponsored by the US Department of Energy (DOE), General Motors (GM) and MathWorks. Argonne National Laboratory (ANL) is managing and organizing this 4-year long competition where 12 North American schools are competing to reengineer a 2019 Chevrolet Blazer. The competition aims to work towards future mobility solutions accounting for automotive trends, like increasing fuel efficiency and establishing SAE Level 2 automation. The developed vehicle will be used for a car-sharing application enabling the changing character of mobility.

The McMaster Engineering EcoCAR or MAC team is participating in its second iteration of the competition. The MAC team is in Year 1 of the competition, which focuses on accomplishing a valid vehicle design. The EMC is putting students into a hands-on training ground providing technical experience in a multi-year vehicle development process covering design, integration and optimizing future mobility solutions. Further years will accomplish total powertrain integration until the end of year 2 and refinements in controls until the end of year 3. Year 4 of the competition is focused on optimizing and establishing a fully functional vehicle including level 2 SAE automation. More detailed information will be provided in Section ”EcoCAR Vehicle Development Process” below. The MAC team has approximately 50 members ranging from first years to graduate students covering most engineering programs. The team is divided into three subteams, namely Propulsion System (PropSys), Control System Modeling and Simulation (CSMS) and CAVS subteam. Each subteam will be supported by a dedicated lead, which must be a graduate student. The lead’s main responsibility is to manage and organize the team and its performance during the year to ensure a successful execution.

1.3.1 EcoCAR Vehicle Development Process

The Vehicle Development Process is accomplished according to the provided EcoCAR Vehicle Development Process seen in Figure 1. Year 1 will be concluded by finishing software verification and starting software validation for future years. It covers defining control system requirements, engineering control system architectures, developing algorithm requirements and developing actual used algorithms and software. Additionally, a propulsion vehicle architecture shall be selected and approved by the competition. The focus lays on developing a fully functional Model-in-the-loop (MIL) system-level simulation model of the team-selected architecture and a functional energy management controller [27].

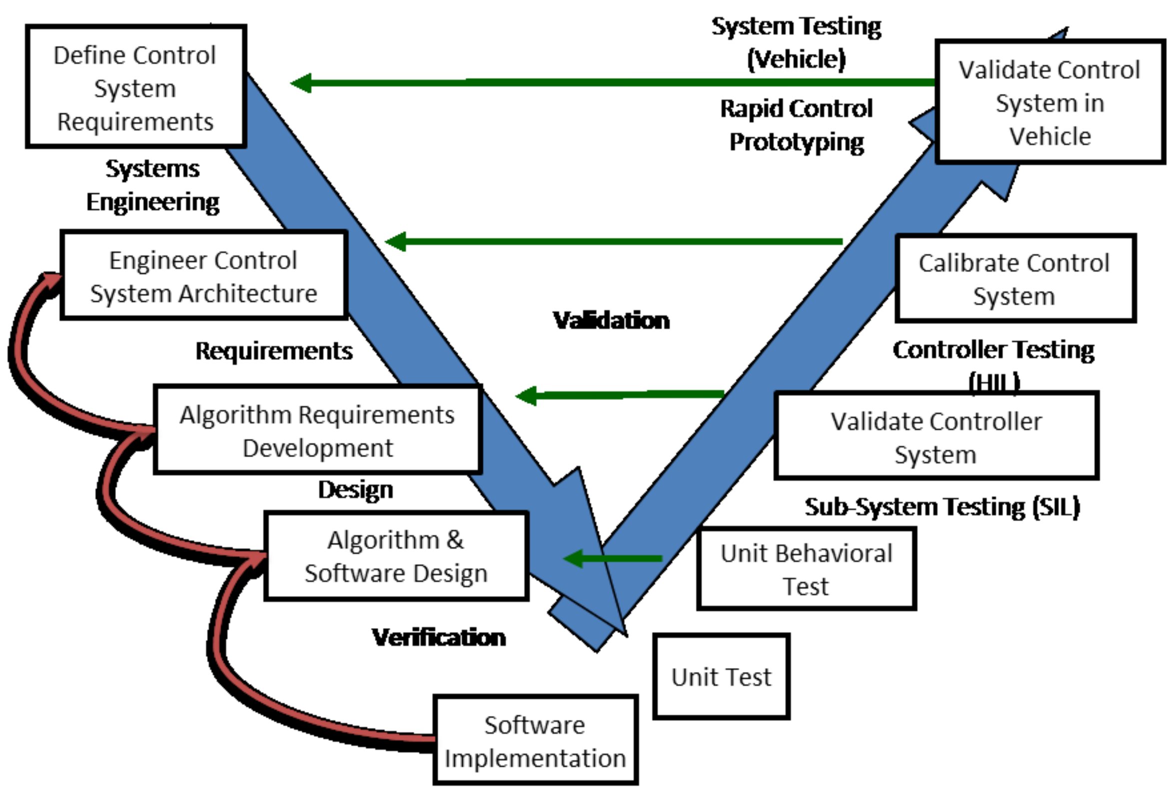

Figure 1: V-Diagram for EcoCAR Vehicle Development Process [27]

1.4 Outline of Thesis

Considering automotive trends and the framework set by the EMC this thesis will be designed around the competition goals for year 1. This includes the development, design, and evaluation of functionality of the control system for the MAC team 2019 Chevrolet Blazer HEV design. Therefore, this thesis will cover necessary fundamental research, the architecture and component selection process, the model development process, the design of the control system from a hardware point of view, the design and development of the energy management strategy or control strategy, and the expected performance once the vehicle is re-engineered based on simulation results. Finally, necessary future work and conclusion of the success of the done research will be shown.

2 Modeling and Control of Hybrid Electric Vehicles: Fundamentals

2.1 Vehicle Modeling

2.1.1 Modeling Methods

According to most of the available simulation, a software distinction must between structural and functional model methods. In the case of HEV modeling accurate functional representation of every component and their interactions is accomplished by used equations representing physical behavior. However, achieving an adequate level of model accuracy can be challenging. Especially for components with two or more energy subsystems. This requires in depth knowledge from different fields of engineering to be combined. Functional methods benefit from increased accuracy and improved system analysis, with downsides in the increased technical knowledge needed [28]. Companies like MathWorks are facing this issue by developing structural model representations with underlying functional based models collected in model libraries. Structural models are predefined masks which are meant to be parameterized according the simulation's needs, mainly with the help of supplier information or datasheet information. Their functionality is validated and documented but is also bounded to the assumptions made by the developer. Within one library interactions between different components is made possible by standardizing Inputs and Outputs (I/O) according to their requirements [29].

Further classification can be made between steady-state, dynamic and quasi-static models. Dynamic models are representing the dynamic behavior of components based on underlying differential equations. For example, the rotational behavior of a shaft is represented by the second order differential equation of rotational motion. Steady-State models are represented by mapping collected data over the chosen inputs of the model. For example, EM and Inverter modeling is based on evaluating the power loss over each time step based on efficiency maps gathered through experimental testing. In this case, a complex dynamic model is not needed. Instead a steady-state model of the EM and Inverter can be used without significant loss of accuracy. Quasi-static models are the combined approach of steady-state and dynamic models. For example, equivalent circuit battery models represent the dynamic behavior of the system voltage, while needed parameters like the OCV-SOC curve and resistance values are based on LUT [30].

The last distinction made is between forward and backward calculating models. Forward and backward refer to the direction in which calculations are performed within a model. In the forward, or engine-to-wheel method, calculations begin with the vehicle torque sources, where transmitted and reflected torque values are applied to the remainder of the model towards the vehicle chassis or other power consumers. In the mechanical domain vehicle speed and rotational speed of the respective components are sent back to the torque sources. Similarly, in the electrical domain current and voltages are used. In the case of a backwards, or wheel-to-engine model approach, calculations begin with the required traction effort at the wheels, and then send this information to the torque sources and other propulsion system components [28]. Backwards model approaches require pre-defined speed drive cycles in order to calculate the force acting on the wheels and therefore calculate the required propulsion system power commands [31].

2.1.2 Model-based Design

According to the provided Vehicle Development Process Model-based Design (MbD) is an important part of the design process. It aims to use virtual prototyping and testing activities to combine system, control and design engineering in an early stage of the development process [32]. It centers around control, signal processing and communications development. Main goals for MbD are building Electronic Control Units (ECUs) including code generation, testing and verification [33]. This process is divided into several testing stages according to the made progress. The below paragraphs describe the main testing stages.

2.1.2.1 Model-in-the-loop

Model-in-the-Loop (MIL) testing is used to verify the accuracy and acceptability of developed vehicle plant models and functionalities. It is necessary to have plant models which can receive control signals and represent component behavior in a sufficient way. According to that controller models need to be built that include working control logic and cover all needed functions defined by set up requirements [34]. No physical hardware components are needed [35].

2.1.2.2 Software-in-the-loop

Software-in-the-Loop (SIL) testing is used to validate the behavior of auto-generated code necessary for ECUs. Embedded software will be tested within the simulation environment but without the interference of any hardware [35]. After validation of the plant model and all functions MIL testing can be considered complete and SIL testing can be started. Generated control code will be tested in the model environment. Correct component I/O is necessary, allow validation against the developed plant model. It can be considered complete after performance on the model is considered sufficient in accuracy and functionality [34].

2.1.2.3 Hardware-in-the-loop

After completed SIL testing a verified ECU is achieved. Nevertheless, developed software has to be tested on the actual component. This process will be done in the Hardware-in-the-Loop (HIL) stage. Testbenches and HIL emulators are used to do HIL testing. For example, developed software for acceleration pedal input conversion will be tested on a testbench including an acceleration pedal and a control unit. Normally, this happens in a closed loop setup allowing verification of developed ECUs in a real-time environment [36]. For automotive systems, the HIL testing stage can be expanded to cover Vehicle-in-the-Loop testing. This stage focuses on ensuring functionality within the target vehicle.

2.1.2.4 Software Development and Requirements

During the software development process, each of the named testing stages needs to be completed successfully. A testing stage can be considered completed when all set requirements over all defined test cases are verified. Depending on the testing stage different requirements need to be developed and managed. A standardized process needs to be established to accompany transitions between testing stages incorporating functionality, feasibility, plausibility and safety aspects.

2.2 Hybrid Electric Vehicle Energy Management Strategy

The following paragraphs clarify problems that energy management system engineers are facing, and the proposed solutions found. Therefore, the different approaches are compared in chronological order to reflect the development process over recent years. Furthermore, it aims to define mathematical boundaries in which a developed control strategy should operate.

2.2.1 Control Strategy approaches for conventional vehicles

Consider an ICE propelled vehicle with an automatic multi-speed transmission. A control strategy can be found to operate the vehicle always in an optimal or close to optimal point. This operation is caused by the simplicity of the considered system. The linear speed of the vehicle and the requested acceleration constrains the power delivered from the transmission output to the wheels. The multi-speed transmission provides the system with one Degree of Freedom (DOF). In that way different combinations of requested torque and selected gear can result in the same amount of power to the wheels. This brings up the opportunity of the control strategy to decide which gears can provide the needed power and further which selected gear operates the powertrain in the most fuel-efficient way [37]. Implemented solutions for automatic multi-speed transmissions are based on the vehicle speed and acceleration pedal position thresholds which can be mapped to a selected gear via a look-up table (LUT). Set limitations are defined based on experience and engineering intuition [38]. Adding more DOFs, through the implementation of a secondary electric power source, allows the propulsion system to be controlled in an even more flexible way. This leads to the problem to find an optimal control trajectory in regard to fuel economy and other outside constraints, such as drivability and battery state-of-charge (SOC), defined as the energy management problem.

2.2.2 The Energy Management Problem

The Energy Management Problem puts the desire of optimal control into an environment solvable with control theory. The following paragraph is about to describe the control of an HEV powertrain mathematically, which makes it possible to apply different control strategy approaches on top of it. This is based on seeing the HEV powertrain in an energy-flow way and putting it into a state system formulation. A time-discrete input sequence of the control vector $u(t)$ must be found in a way that satisfies chosen targets. Fulfilling those targets are realized by minimizing the performance index J over a given optimization horizon $[t_o, t_f]$ where t_o represents a starting point and t_f an ending point in time. The performance index J will be defined as follows [39]:

Equation 1 : Performance Index

$$J\left(x(t_o), u(t), x\left(t_f\right)\right) = \phi\left(x(t_o), x\left(t_f\right)\right) + \int_{t_o}^{t_f} \mathrm{L}(x(t), u(t), t)dt \qquad \text{(Equation 1)}$$

Where t is denoted as the current time step, $u(t)$ as the inputs of the control vector, $x(t)$ as the state variable, $\mathrm{L}(\cdot)$ as the instantaneous cost function and $\phi(\cdot)$ as the terminal cost. An optimal control law, denoted as $u^*(t)$, follows a state trajectory $x^*(t)$ corresponding to optimal control. Optimal control is defined as the chosen control input $u^*(t)$ resulting in the most minimized performance index J.

Equation 2: Optimal Control Law

$$J\left(x(t_o), u(t), x(t_f)\right) \geq J\left(x(t_o), u^*(t)\,, x^*(t_f)\right)$$

(Equation 2)

$$\forall\, u(t) \neq u^*(t)$$

In regard to HEV architectures, the control input $u(t)$ and state variable $x(t)$ defines what should be controlled and with which physical quantities an optimal control trajectory is achieved. Depending on the chosen state variables the dimension of the state variable vector varies and can be described as follows:

Equation 3: State Variable Vector Definition

$$x(t)\ \epsilon\ \mathbb{R}^n$$

(Equation 3)

$$x(t) = \{SOC_{HV}(t), SOC_{LV}(t), FE(t)\}$$

Where n describes the number of state variables, $SOC_{HV}(t)$ describes the high voltage (HV) SOC, $SOC_{LV}(t)$ describes the low voltage (LV) SOC and FE describes the fuel economy over time. The most commonly used state variables are the fuel consumption of the ICE and the SOC of the used battery pack. More specifically, an HEV can operate with two different voltage levels, which expands the dimension of the state variable vector to three, including two SOC variables, one describing the SOC of the HV battery pack and one describing the SOC of the LV battery. All these state variables are influenced by the physical quantities included in the control vector shown below:

Equation 4: Control Vector Definition

$$u(t) \in \mathbb{R}^m \qquad \text{(Equation 4)}$$

Where m describes the number of control variables. The control vector has the same dimension m as the number of degrees of freedom (DOF) of an HEV powertrain represented in an energy-flow diagram. Most often used are the power quantities of the different energy flow paths. Constrained by the linear speed of the vehicle, which is considered an external input, only the torque requested can be used to control the power. Following that the requested torque from every power source, such as the ICE o EM, are the dimensions of the control vector. In some cases, the requested torque by a Belted Alternator Starter (BAS) motor can be included. Additionally, the selected gear and clutch status must be included into the control inputs because these parameters influence which power sources are connected to the wheels and how the requested torque will be transformed for example by the multi-speed transmission.

Equation 5: Control Vector for HEVs

$$u(t) = \{T_{ICE}(t),\ T_{EM}(t),\ T_{BAS}(t), n_{Gear}(t), n_{Clutch}(t)\} \qquad \text{(Equation 5)}$$

Once all state and control variables are defined a target for the performance index needs to be defined. In the automotive sector the target is mostly to minimize fuel consumption. Following the target of minimizing fuel consumption the instantaneous cost function needs to describe the dynamics L(·) of fuel consumption. Depending on the level of accuracy other factors can be included in L(·) like an emission value over time, battery wear over time or equivalent fuel consumption. Simultaneously the system dynamics show how the state variables change according to the control inputs. Those system dynamics can be solved purely mathematically or more commonly by a simulation approach modeling the powertrain dynamics in simulation software. Further initial and terminal state values have to be defined. The terminal cost describes the difference of the states over the driving operations and respectively the change of the amount of energy inside the system. If they differ from each other the terminal cost appears to be unequal to 0. Regarding that charge sustaining mode is aiming for a terminal cost equals to 0 for the state variable of the SOC. This means initial SOC and terminal SOC should be equal.

Equation 6: Initial and Terminal State Definition

$$x(t_o) = x_o \;\; x(t_f) = x_f \qquad \text{(Equation 6)}$$

To avoid unrealistic state switching while finding the optimal control trajectory, control limitations have to be defined. For example, to avoid overvoltage and undervoltage of the battery pack. Another example are instantaneous control limitations, like the maximum and minimum power which can be requested by each single powertrain component.

Equation 7: Control Limitations

$$x_{min} \leq x(t) \leq \; x_{max} \qquad u_{min} \leq u(t) \leq \; u_{max} \qquad \text{(Equation 7)}$$

It is necessary to develop the corresponding control system based on the chosen HEV architecture and control strategy. Overall describing the energy management problem defines the boundaries that the control strategy should work within [39].

2.3 Control Strategy Approaches and Tools

A control strategy for an HEV must sufficiently solve the Energy Management Problem in regard to fuel consumption. The most common approaches are investigated in the following paragraphs. Namely heuristic approaches, rule-based (RB) or fuzzy logic-based strategies, instantaneous minimization approaches, like equivalent consumption minimization strategy (ECMS) and local and global optimization approaches, like Dynamic Programming (DP) or approaches including machine learning techniques. Further, these strategies are divided into offline and online methods. Online methods are calculated and solved with the computational power of the microcontrollers inside of the HEV. Offline methods require more computational power and therefore will be calculated outside of the HEV. The limiting factor causing this classification is the computational power inside the HEV.

2.3.1 Heuristic Control Strategies

2.3.1.1 Rule Based Approaches

RB and most other approaches operate in two different modes depending on the desired final SOC, namely Charge Sustaining (CS) or Charge Depleting (CD) mode. To achieve these modes RB approaches, follow a simple “If-Then” structured algorithm called an event triggered algorithm. Based on engineering intuition several rules are set to operate the HEV powertrain in a way that is proven to work sufficiently but not necessary in an optimal way. Main decision factors are the SOC, the linear vehicle speed and the requested power. After deciding whether to operate in CS or CD mode the control strategy has to decide how to operate the vehicle while accomplishing the requested power demand. This will be done by defining the torque split and the used components.

Specified event triggers are used to determine the vehicle operation. Most common events are hard acceleration, low acceleration, braking, regenerative braking, recharging, reverse, start and stop [40]. For example, hard and low acceleration can be achieved with the same used components but with a different calibration. In this case, the operation will vary in the applied torque split which will be different for both situations. Gear selection will be provided by using either a predefined shifting schedule based on the efficiency of each gear or even more simplified by observing only the actual linear vehicle speed. In conclusion, a decision has to be made to choose between CS or CD mode, the used components, the applied torque split, and the selected gears based on the specific event triggers occurring.

2.3.1.2 Fuzzy Logic Approaches

Fuzzy Logic approaches are similar to RB approaches but instead of using hard constraints like switching between driving modes at certain SOC, torque or pedal position, soft constraints are used. This allows a smoother and slightly adaptive switch between different events. Inside a Fuzzy Logic approach chosen inputs are analyzed, scaled and outputted. Membership functions of different states allow calculating, for example, a smoother change of torque split to obtain better efficiency for one propulsion component. Fuzzy Logic controls enable a range of options within the control strategy to find a more optimal solution as compared to RB. The main benefit of Fuzzy Logic Approaches is the possibility to tune an existing RB approach to operate selected components in a more efficient way. However, optimizing two or more components in this way can lead to suboptimal behavior of all components. Facing this problem, a solution found is using a dynamic programming (DP) approach or an optimization algorithm like a genetic algorithm (GA) to help define smoother switching. RB and Fuzzy Logic approaches are considered online methods

[41] [42], but using DP to tune RB and Fuzzy Logic approaches needs to be done offline due to the high computational power required. Overall these methods are considered online but need to be tuned with offline tools.

2.3.2 Instantaneous Minimization Control Strategies

2.3.2.1 ECMS approaches

An ECMS approach is designed to minimize a given cost function. Since an HEV has two or more power sources a comparable quantity has to be defined which allows comparing the fuel consumption of the ICE and the electrical energy used inside the battery pack. This quantity is defined as the equivalent fuel consumption, which adds up the fuel consumption of the ICE and equivalent fuel consumption of the electrical powertrain. The equivalent fuel consumption results out of the product of the battery energy used multiplied with an equivalence factor. This equivalence factor is necessary to make both energy sources comparable to each other Additionally, a charging and discharging penalty can be added to achieve CS or CD modes in a defined SOC range [39]. The cost function can be expanded by other targets to consider more aspects worth observing, like emission outputs or drivability aspects [43].

Equation 8: Equivalent Fuel Consumption

$$J_{Fuel} = \int_{t_o}^{t_f} \dot{m}_{f,eqv}(t)\, dt$$

(Equation 8)

$$\dot{m}_{f,eqv}(t) = \dot{m}_{ICE}(t) + f_{Pen,SOC} * S_{Chr/Dis} * \dot{m}_{EM}(t)$$

$$\dot{m}_{ICE}(t) = \frac{P_{ICE}}{H_{LHV} * \eta_{ICE}} = \frac{n_{ICE} * T_{ICE}}{H_{LHV} * \eta_{ICE}}$$

$$\dot{m}_{EM}(t) = \frac{P_{EM}(t)}{H_{LHV} * \eta_{EM} * \eta_{Con} * \eta_{Bat}} = \frac{n_{EM} * T_{EM}(t)}{H_{LHV} * \eta_{EM} * \eta_{Con} * \eta_{Bat}}$$

Where $\dot{m}_{ICE}$ is denoted as the fuel consumption of the ICE, $\dot{m}_{EM}$ as the fuel consumption of the EM, $f_{Pen,SOC}$ as the SOC penalty factor, $S_{Chr/Dis}$ as the equivalence factor for either charging or discharging and H_{LHV} as the lower heating value of the fuel used by the vehicle. Main improvements in current publications are made by tuning the equivalence factors, the SOC penalty or determining the minimum cost function value [44] [45]. It is possible to use the Pontryagin's Minimum Principle whenever an optimal operation point of a system has to be found [46].

2.3.2.2 Adaptive ECMS approaches

Adaptive ECMS approaches utilize either vehicle and component feedback or offline optimization methods to adjust parameters depending on the driving mission online. Based on research, the optimization problem should be shifted to the simplest possible factor. This is due to the increased mathematical complexity going hand in hand with a more complex optimization problem. For example, it is deemed to be feasible to find an optimal equivalence factor online where as finding an optimal torque-split can be challenging. On the one side these feedback approaches can be realized by knowing a priori state. On the other side a predictor can be used to gain information about future states of the vehicle to adjust to these conditions. One example for predictor approaches is model-predictive control, which estimates a disturbance vector within a prediction horizon in combination with DP to calculate the optimal control law applied on a shorter application horizon. More general predictor and estimator methods can use either all or any combination of past, present and future driving data available from the vehicle [38] [40].

2.3.3 Optimization Methods

Different optimization methods can be used to support an existing control strategy approach. According to other publications, these tools are classified as an independent control strategy whereas inside of this thesis they are considered supportive tools [42]. Seeing current applications, the computational effort of that approach is deemed too high to be implemented online. Nevertheless, these methods are used to support existing control strategies by computing internal optimizing processes.

2.3.3.1 Dynamic Programming

DP will be used as a global optimization tool. It requires a given global optimization horizon, as reference data, to perform an optimization. This global optimization horizon cannot cover every operating point the vehicle will face during its lifetime. Rather those optimization methods are considered global in regard to knowing the driving operations for one or more drive cycles in its entirety. This is applicable because emission and fuel consumption values are made comparable through standardized drive cycles such as NEDC or FTP75, where reasonable computational power can be used to find an optimal solution. These methods are often used to generate a reference for testing existing control strategies to validated against. Due to high computational power, constant efficiencies for components should be assumed to decrease the computational load. A balance needs to be found between model accuracy and reliability of model results [47]. For example, during DP every single combination on how to achieve the same output torque with different torque split is evaluated backward in time for each possible SOC inside a defined range. A cost function is used to reach a minimum state of equivalent fuel consumption. Afterward a backward evaluation, following the trajectory of the minimum cost over the SOC is applied. The optimal torque split found results in optimal equivalent fuel consumption and can be implemented with a LUT. Other parameters like the equivalence factor or the amount of regenerative braking can be determined in the same way. Other approaches, like stochastic DP, attempt to limit the number of possible combinations, and therefore the optimization horizon, to reduce computational load. A probability distribution is set to calculate the operations which are most likely to appear. Using this, an approach is made to implement it as an online optimization method for supporting an existing ECMS approach [44].

2.3.3.2 Machine Learning Methods

Nowadays machine learning methods are mainly used to operate as a predictor. For example, Neural Networks (NNs) can be used as a predictor to adjust several parameters like the equivalence factors of an ECMS, as for example in an adaptive ECMS approach. However, even more information from past and present states of the vehicle can be used. For example, past driving conditions, like average velocity and standstill time, and present driving conditions can be used to recognize the driving pattern used to adjust the control strategy. Future driving conditions can be predicted but are considered complex as a good knowledge of the disturbance vectors is required. It is impossible to estimate the whole disturbance vector because it includes too many uncertainties. However, a small part of the disturbance vector can be predicted [48]. It is worth mentioning that machine learning methods contain a huge potential to not only operate as a predictor. Moreover, it can be used to substitute optimization methods by learning from real driving data.

2.4 Energy Management Strategies for Parallel-Through-The-Road Hybrid Electric Vehicles

Based on available research most implemented energy management strategies are focusing on heuristic approaches including RB and fuzzy logic ones. Other approaches like ECMS and machine learning approaches are researched but are considered to be too specific to be applicable for this research [49] [50]. Moreover, feasible control strategies are investigated allowing to find the best possible solution for the team selected architecture and goals.

Most commonly seen is a rule-based deterministic control approach named “Electric Assist Strategy”. Based on a speed and engine efficiency threshold the vehicle will be operated by the EM only. This tries to reduce the amount of time the engine is operated in an inefficient manner. Once those thresholds are exceeded the vehicle will operate only by the engine. Based on the maximum available engine power, the motor will fulfill power commands exceeding the engine capabilities, operating the vehicle with the engine and the motor. Once the defined lower SOC level is approached the engine is used to provide additional charge power causing the battery to recharge again to a defined level. This is based on the deviation of the actual SOC to a set target SOC multiplied with a tunable charging factors to gather a charge torque command [51]. Other research is multiplying the current engine speed with the tunable factor and the SOC difference to obtain a charge power command instead of charge torque command [52]. Improvements of this approach can be seen by calculating an optimal engine torque which operates the engine at its most efficient point while the EM is used to supply the difference between the commanded torque and the optimal engine torque. Optimal engine torque can be determined by the normalized engine efficiency, and if desired, the amount of GHG emitted. This data is stored in a LUT and can be referred to as the Optimal Operation Line [53]. Beside using the Electric Assist Strategy" a "Torque-Leveling Threshold-Changing" approach can be followed [52]. This approach requests a constant torque level from the EM which will be modified based on the difference of the actual SOC and a target SOC as well as the difference between a set engine speed and the actual engine speed. Two tunable parameters are used to weight the effects of the SOC difference and the speed difference. If these parameters are tuned proper charge sustaining operation is ensured.

Fuzzy Logic control approaches showed to use the concept of Optimal Operating Line to set up a membership function which allows modifying the optimal torque based on the required torque and the SOC. It outputs the modified engine torque where the EM is supplying the additional torque to fulfill the total torque request [51]. Different fuzzy logic approaches are splitting up the optimal torque calculation and the fuzzy logic controller. In that way the optimal torque calculation can be influenced based on different demands from the engine as for example, most engine efficient calculation or most fuel efficient calculation [54]. Additional it allows to add more information like for example gradeability into the membership function [53].

It can be seen that most approaches are focusing on operating the engine as close as possible to its optimal operation point where only torque support with the rear powertrain is assumed. Additionally, all investigated research assumed that the engine can provide a charging opportunity by an alternator to recharge the battery pack towards a set target SOC.

2.5 Summary

A quick summary of fundamental vehicle modeling approaches, Model-based Design and the energy management problem as well as commonly found solutions, was given. This was done to support necessary decisions, which needs to be done while developing the vehicle model, developing a control strategy and structuring the workflow of the CSMS team. Firstly, for vehicle modeling it was important to gather an understanding of different model approaches and how to distinguish between them. The focus lays on a functional representation, where additional simulation needs can be fulfilled by developing equation-based models or subsystems. Secondly, research on Model-based Design focused on the applicability to the resources available to the MAC team, such as the dSPACE HIL emulator or the used dSPACE microAutoBox II. An iterative process was chosen accompany development through MIL, SIL and HIL testing. Lastly, control strategy approaches were investigated to gather more insight into complexity and possibility to adapt to unknown situations. It could be seen that increased complexity is not necessary correlating with increased fuel economy. The control strategy should be adapted to the selected architecture to maximize its impact on fuel economy.

3 McMaster Engineering EcoCAR Vehicle Architecture Selection

Guiding the team towards a feasible architecture was a task that the myself as the CSMS lead had to face. Main challenge during this process was to set up a simulation tool including all possible architectures and components that can be utilized by the team. A preselection of feasible components and their implementation into the vehicle model was done by me. Therefore, reliable component data had to be found, processed and implemented. Preferred architecture options were modeled and included. Afterwards a simplified control strategy was implemented and made compatible with all architectures and components. Once the simulation tool was finished, I provided the model to the team with necessary training on basic vehicle dynamic modeling and performance and fuel economy evaluation. The following paragraphs are summarizing the model development and how the competition limitations are implemented by the CSMS lead and the found conclusions by the team.

3.1 Competition and Team Environment

The goal of the competition is to re-engineer a 2019 Chevrolet Blazer by partially electrifying the powertrain and adding autonomous features. Additionally, the vehicle should suit into a defined target market, which is set up around a Mobility-as-a-Service application. The competition Vehicle Technical Specifications (VTS) target at least 15% improvement in fuel economy while maintaining stock performance characteristics like IVM-60 mph time and braking distance. Table 1 shows the most important competition's performance and fuel economy targets excluding design requirements like curb mass, ground clearance and passenger capacity.

Table 1: Competition and Team VTS

Specification	Unit	Competition Target	Team Targets
Acceleration, IVM–60 mph	[s]	7	7
Acceleration, 50–70 mph	[s]	6.5	6.5
Braking, 60–0 mph	[ft]	138.4	138.4
Gradeability (at 60 mph for 20min)	[%]	3.5	3.5
Vehicle Top Speed	[mph]	80	80
Total Vehicle Range	[mi]	250	250
Fuel Economy Improvement	[%]	15	15

Lessons learned from the EcoCAR3 competition have shown that VTS decisions made in early design stages often highly differ from the actual achieved VTS in year 4. Therefore, the team decided to keep target VTS similar to the minimum competition VTS. However, according the made progress VTS targets can be updated after year 3.

The team tried to reflect its strength and weaknesses in the selected architecture. Strong emphasis was set to generate a vehicle that will suit the team's target market. Additionally, it was deemed to be important that the chosen architecture can be realized by the team within year 2 of the competition. On the one hand the lack of hands-on experience of the team prioritizes a simple to implement architecture. While on the other hand, strong electrical and control system and modeling knowledge were detected within the team. Both points together formed a team requirement that aims for simple mechanical integration while focusing on advanced electrical features and innovation in the control system, modeling and simulations team. Connected Automated Vehicle System (CAVS), a newly introduced subteam, influenced the vehicle design marginally due to little knowledge about the necessary features. Nevertheless, the team's architectures should be able to support SAE level 2 automation to improve fuel economy through the implemented CAVS features. In conclusion, the team tries to connect the above defined requirements to the found target market.

3.2 Target Market Research

The EMC set some limitations in which the teams can develop and define their target market. It requires a production-ready vehicle designed for the use in a carsharing fleet. This means that that the target market has to be defined over a fleet owner and a customer. Both represent different interests and have to be combined within the set VTS requirements and the selected architecture. All decisions made during the vehicle design process have to be tied back to the target market.

The MAC had to define a location for car-sharing services. Due to the proximity of McMaster University to Toronto and the Greater Toronto Hamilton Area (GTHA) this area particularly qualifies for further investigation. The population of the GTHA is approximately 6.85 million people over an area of 8,262km^2, which makes it the highest population area in Canada [55] [56]. Roughly one in four family households in the Toronto area do not own a vehicle [57], which brings a large opportunity to open a new market. The GTHA shows a high need for commuting due to the centralized job market in the downtown area of Toronto and the simultaneously increasing price of living in the same area [58]. This forces people to move to suburban areas, where living is affordable and furthermore forces them to commute between their homes and their workplace. It was concluded that large population density, low vehicle ownership rates, increased traffic, as well as the increased need for commuting in the GTHA would suit a car-sharing service.

Next to discuss is the socioeconomic demographics and physiographic influence of the observed areas and its inhabitants. Since 2006 the fastest growing demographic in the GTHA is millennials [59]. They are mainly students or young professionals with post-secondary education, expecting an average income of around $54,000 CAD [60]. As mentioned above, the low income forces them to support the trend of commuting between suburban and urban areas. According to an online survey done by the team, millennials are willing to accept car-sharing services and advanced CAVS feature, if it suits their needs of everyday life. Also increased awareness of environmental protection was seen throughout the survey.

In conclusion, the defined fleet owner should operate a successful carsharing service within a the GTHA, paying attention to the urban and suburban characteristics. It is proposed to use a mixed carsharing model offering free-floating and stationary vehicles to maximize usage and flexibility of the fleet vehicles while providing mid-level cost for the fleet owner. The main customers as defined are millennials living in the GTHA, embodying suburban and urban transportation needs. Their willingness to accept CAVS features and the raised awareness of environmentally friendly transportation was deemed to be important. Marketing will focus on millennials, but the developed service is open to all sociodemographic groups. As mentioned above the team is constantly reiterating the VTS targets. Based on the defined target market the team prioritized fuel economy over urban driving and commuting. Performance requirements are ranked lower but should at least fulfill minimum competition requirements.

3.3 Architecture Selection Process

The architecture selection process consisted of two decisions. Firstly, the team's architecture and secondly the used components. The competition is providing several GM sponsored components including the GM Malibu Battery Pack and five different powercubes, where a powercube consists of a GM engine and a connected GM transmission. GM will provide full support for powercube and battery pack implementation as long as no mechanical modifications will be made. Teams are allowed to use different engines or split up the powercubes but as a result will not get any support from GM. Several other competition sponsors are offering components such as EM, battery packs, drive units or power inverters. Beside that teams can acquire components through purchasing or team sponsoring. Lastly, the competition does not allow custom team-built battery packs.

3.3.1 Architecture Variants

The team planned to rely on implementation support from GM for the powercube. Therefore, engine and transmission options are limited to the five provided powercubes and will not be split up. This means P2 and P3 motor placements on the front axle cannot be considered. P4 placements on the front axle were deemed to be unrealistic due to packaging issues in the engine bay. Further, former experience and failure in shaft stability with P1 motor placement drove the decision to not further investigate that option. Nevertheless, belted P0 and P4 motor placement on the rear axle and every combination of those two were considered to be valid architectures worth considering in more detail. For visualization, Figure 2 summarizes all common motor placement options. It is worth mentioning that a P4 motor placement can be done in single or dual motor configuration.

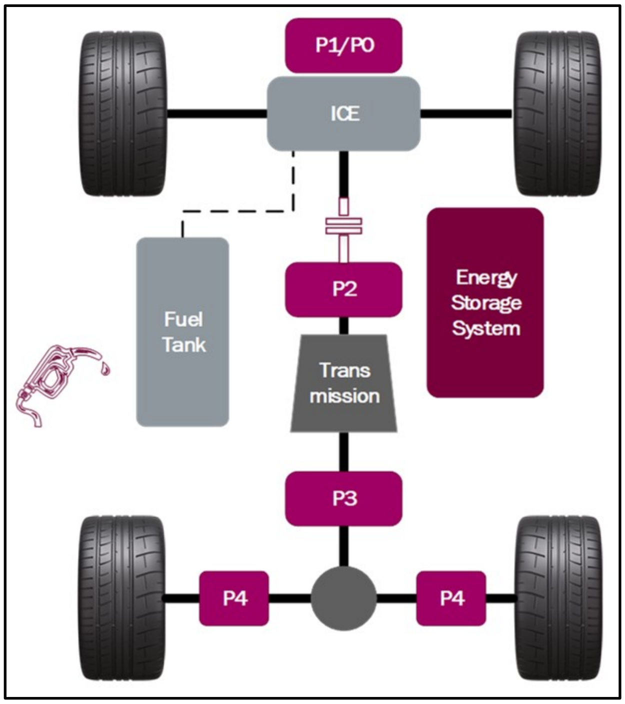

Figure 2: Motor Placement Options

3.3.2 Component Variants

3.3.2.1 Powercube

GM is providing five powercubes consisting of combinations of three engines, namely the LYX, LTG and LCV, and five transmissions, namely the M3U, M3D, M3E, M3H and M3D. Differences between engines are the displacement volume and the intake system, which can be turbocharged or naturally aspirated. All transmission options are 9-speed transmissions and can either have an accumulator, an Electronic Transmission Range Selection (ETRS), both or neither. All powercubes are summarized in Table 2 below.

Table 2: Powercube Options

Powercube Options	Engine			Transmission			
	RPO Code	Displacement Volume	Intake System	RPO Code	Number of Gears	Accumulator [Y/N]	ETRS [Y/N]
1	LYX	1.5L	Turbocharged	M3U	9	Y	Y
2	LTG	2.0L	Turbocharged	M3D	9	Y	N
3	LTG	2.0L	Turbocharged	M3E	9	N	N
4	LTG	2.0L	Turbocharged	M3H	9	Y	Y
5	LCV	2.5L	Naturally Aspirated	M3D	9	Y	N

Engine options can be further broken down into their physical quantities like peak power or peak torque. However, this is confidential data and therefore will not be discussed. From preliminary simulation, it can be stated that all powercubes can follow both EMC drive cycles sufficiently.

3.3.2.2 Battery Pack

Initially the competition did not allow any battery pack except the GM Malibu Hybrid pack. Throughout year 1 of the competition a sponsorship for custom battery pack was made available to the teams. The second available battery pack will be developed together with interested schools and made available afterwards to be purchased. The team decided to go with the GM Malibu Hybrid battery pack to avoid points of conflicts with other schools during the design process and the additional cost related with the pack. The GM Malibu Hybrid battery pack is a power-oriented pack which particularly should be used for mild hybrid applications. It offers 52kW discharge and 65kW charge power and a stored energy amount of approximately 1.5kWh.

3.3.2.3 Rear Electric Motor

The team considered three possible rear electric machines for the P4 position. The first option was the Bosch SMG 180/120 sponsored by Bosch for the competition. It is uncertain how many units they will offer, and in case of conflicts a ranking by the competition is done to decide who will receive the sponsored units. The second option is the YASA P400. The team used the same EM during the EcoCAR3 competition and therefore has the component in-hand. The last option is the Plettenberg Nova 30. Similar motors were used for the former MAC Formula Hybrid vehicle. Therefore, the former collected experience could be utilized. It was considered that the Bosch and the YASA EM will be used in a single motor configuration using a differential, while the Plettenberg motor will be used in a dual motor configuration without a differential. Main characteristics of all motors can be seen in Table 3.The Bosch and Plettenberg motor data were gathered from the available datasheet, where YASA data was gathered through in-house testing done in EcoCAR3.

Table 3: Motor Options

Motor Options	Limitation				Operation Voltage
	Peak Power	Cnt. Power	Max. Torque	Max. RPM	
Bosch SMG 180/120 [61]	80 kW	40 kW	200 Nm	12.800 RPM	270 V
YASA P400	90 kW	75 kW	250 Nm	7.500 RPM	400 V
Plettenberg Nova 30 [62]	30 kW	15 kW	80 Nm	7.000 RPM	140 V

3.3.2.4 Belted Alternator Starter Motor

For the P0 motor position two different Belted Alternator Starter (BAS) motors were investigated. On the one hand the sponsored Denso HV BAS and on the other the Valeo i-StARS LV. The main difference is the applied voltage level. The Denso BAS motor functions on a HV level with voltages of 300V, which would connect it to the GM sponsored Malibu Hybrid pack. The Valeo i-StARS works at LV levels, which are traditionally settled around 10V to 20V and therefore can be powered with the LV battery in the car. The Valeo i-StARS will be sponsored to the team by Valeo along with technical support for implementation and controls. Table 4 compares both components according to their main characteristics.

Table 4: BAS Options

BAS Options	**Limitation**				**Operation Voltage**
	Peak Power	Cnt. Power	Max. Torque	Max. RPM	
Denso HV BAS [63]	30 kW	12 kW	60 Nm	21.000 RPM	300 V
Valeo LV i-StARS Gen. 3	4 kW	3 kW	75 Nm	18.000 RPM	12 V

3.3.2.5 Other components

The team made a decision to design a rear powertrain consisting out of the selected P4 motor, and if applicable, a clutch, a team-built gear reduction, and a differential. These components will be either purchased through GM or suppliers, are available from EcoCAR3 or will be manufactured according to the team developed design. The selected clutch is the Tilton 5.5” OT-III Metallic Racing clutch in two-plate configuration with orange springs. Former experience and the maximum allowable transmitted torque were key factors for choosing that clutch. The selected differential is the differential from the EcoCAR3 2013 Chevrolet Camaro due to its availability and feasibility for packing the overall rear powertrain. The clutch and differential would suit the Bosch and the YASA motor, while the Plettenberg motors are not in need of these. The planned gear reduction for the Bosch and YASA motor will be a single speed helical one, where as the gear reduction for the Plettenberg motors would be planetary gearset.

3.3.3 Available Options

In a preliminary state all possible combinations between motor position options, powercube options, EM and BAS motor options were compared in a simplified model allowing a comparison towards a minimum valuable product.

A minimum valuable product was defined as achieving competition performance and fuel economy target. Necessary implemented functions were, if applicable Start/Stop applications with the BAS motor, regenerative braking and supportive actions with the rear EM. A rule-based control strategy developed by MathWorks was utilized. Mentioned simulations below were done with all powercubes options.

Firstly, P0 architectures were investigated. Designs from EcoCAR2 competition have shown that a HV 30kW BAS motor would need a well-designed Front End Accessory Drive (FEAD) to utilize it the full power of it. This is accompanied by high risk in failure and implementation of that component. The team design of a belted system, being able to transport the resulting torque peaks sufficiently, is deemed highly risky. The team was not willing to take that risk. Using solely the Valeo i-StARs system it was conducted that necessary fuel economy improvements will not be achieved. Preliminary simulation and discussion with Valeo confirmed that. Secondly, P0-P4 architecture investigation showed that both BAS options in combination with the rear EM options are worth researching. In this preliminary stage it was assumed that the BAS motor is only used for Start/Stop application and minor acceleration support actions, which makes the HV Denso BAS motor available again throughout the decreased power necessary. Nevertheless, the use of the HV Denso BAS motor was decided to be problematic due the necessary LV system design and the limited energy inside the GM Malibu Hybrid battery pack. In that case the HV Denso, the rear EM and a DC-DC converter were assumed to be connected to the GM Malibu Hybrid pack. The DC-DC converter was necessary to supply the vehicle with LV for necessary loads caused by the control system and CAVS. Simulations have shown that the applied LV loads are discharging the GM Malibu Hybrid battery pack to a degree where most of the recovered energy from braking will be used for ensuring charge sustaining (CS) and resulting in no to little fuel economy improvements. P0-P4 architectures utilizing the Valeo i-StARS system with a separated LV system from the HV battery pack and any rear EM showed sufficient fuel economy improvements and will be further investigated. Lastly, all P4 architectures were decided to be realistic but were resulting in less fuel economy improvement in comparison to the P0-P4. This is caused by the missing Start/Stop functionalities.

Table 5 summarizes all considered architectures and component options and their validity. Combinations marked valid are considered in an energy consumption study evaluation to define three possible architectures to accompany the development process of year 1.

Table 5: All considered architectures and component options

Combination	Architecture	Powercube Options	EM Options	BAS motor Options	Valid [Y/N]
1	P0	1/2/3/4/5	-	Denso HV	N
2	P0	1/2/3/4/5	-	Valeo i-StARS	N

3	P4	1/2/3/4/5	Bosch MG 180/120	-	N
4	P4	1/2/3/4/5	YASA P400	-	N
5	P4	1/2/3/4/5	2x Plettenberg Nova 30	-	N
6	P4-P0	1/2/3/4/5	Bosch MG 180/120	Denso HV	N
7	P4-P0	1/2/3/4/5	YASA P400	Denso HV	N
8	P4-P0	1/2/3/4/5	2x Plettenberg Nova 30	Denso HV	N
9	P4-P0	1/2/3/4/5	Bosch MG 180/120	Valeo i-StARS	Y
10	P4-P0	1/2/3/4/5	YASA P400	Valeo i-StARS	Y
11	P4-P0	1/2/3/4/5	2x Plettenberg Nova 30	Valeo i-StARS	Y

3.4 Energy Consumption Studies

The team leads decided to open the architecture selection and the accompanying energy consumption studies to the whole team. This is done to ensure that the future team can identify themselves with the vehicle. The team got divided into three architecture teams with a similar number of members from each subteam. Each of the three architectures had to follow a defined characteristic, which were set by the team leads. Architecture 1 was defined to be a safe architecture, which should be able to hit all fuel economy and performance requirements. It should be low risk and low reward. Architecture 2 was defined to be an "efficient" architecture, which when execute perfectly should have the ability to hit all requirements in an outstanding way. It should be rated medium risk, high reward. Architecture 3 was defined to be an innovative architecture, which should achieve all requirements in an unconventional way. It should be rated high risk, high reward. Myself in the role of the CSMS lead did set up a preliminary model including all valid components and architectures. The architecture teams were offered this model together with a pattern search optimization algorithm to support and defend their decision for the architecture and component selection.

3.5 Final Architectures

In Table 6 all three found architectures and their identities are shown. The team's choices were based mainly on the energy consumption evaluation done by the architecture teams, their engineering judgement and component experience. The chosen architecture for all variants is a P4 Parallel-Through-the-Road where the front powertrain varies in the used powercube option. The rear axle powertrain for Architecture 1 and 2 will be single motor configuration together with a single speed gear reduction and a clutch added in front of the differential. The rear powertrain for Architecture 3 will be dual motor configuration using one single speed gear reduction per motor and no differential. All architectures are using the LV Valeo i-StARs BAS motor and the GM Malibu Hybrid battery pack. Architecture 1 and 3 are using powercube option 3, including the

2.0L LTG engine where as Architecture 2 is using powercube option 1, including the 1.5L LYX engine. Architecture 1 and 2 are using the YASA P400 and Architecture 3 is using two Plettenberg Nova 30 motors. The Bosch SMG 180/120 was deemed to not suit the team’s architecture.

Based on a team internal ranking, the “efficient” architecture was decided to be the favorite, the “safe” architecture was defined as the second choice and the “innovative” architecture placed third. Therefore, vehicle model development focused more on representing the “efficient” architecture and from now on will be referred to as the team’s architecture. The competition approved that architecture and therefore will be realized in the following years.

Table 6: Architectures for Architecture Selection Process

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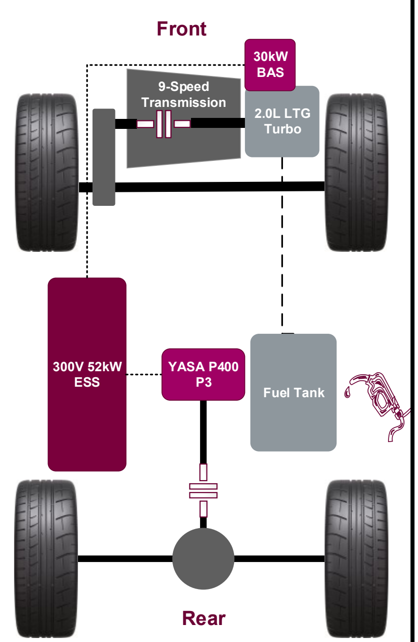
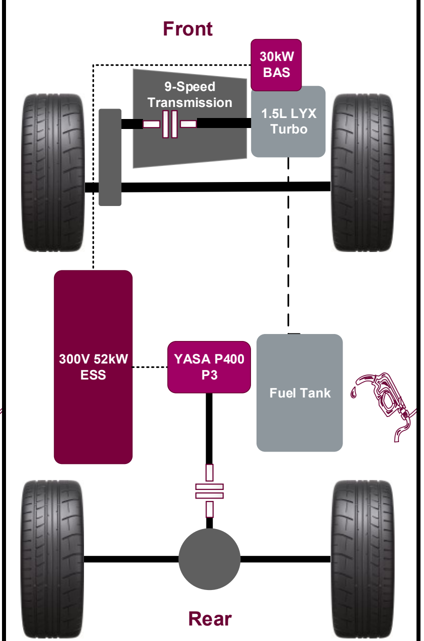
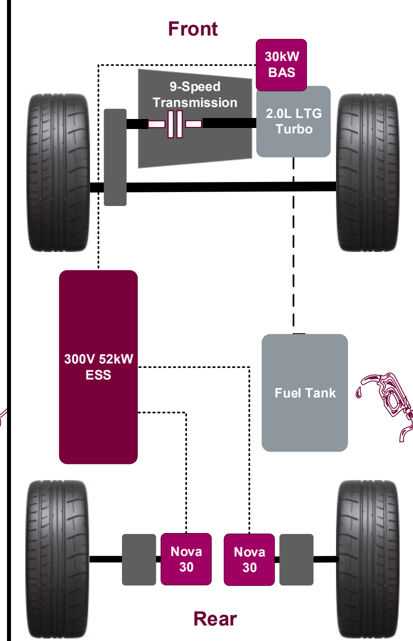
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>2) Safe architecture</td><td>1) Efficient architecture</td><td>3) Innovative architecture</td></tr>
</table>

3.6 Summary

The architecture selection process was mainly driven by the set limitations of the competition and the team's strengths and weaknesses. Strong electrical and control system knowledge should be utilized, while having a simple mechanical implementation. Also, the team's architecture should fit into the defined target market for a MaaS application in the GTHA, targeting urban and suburban transportation needs. It is assumed that this service will be mostly used by "Millennials". However, this service should be available to everybody with an increased environmental awareness.

An architecture was chosen that focus on fuel economy improvement and a low cost of ownership. The selected P0-P4 Parallel-Through-The-Road architecture allows that both axles can be operated independently, which is useful in case of an unplanned mechanical failure or similar during development or even during driving. Missing knowledge in FEAD design to connect the BAS motor is mitigated by working closely together with the BAS motor supplier to design the whole system. The planned rear powertrain is focused on high-power operation and is deemed to be feasible in realization through former experience with most of the used components.

4 Vehicle Model Development

During the vehicle model development decisions about the model environment and framework, used model method, and the implementation had to be made. As the CSMS lead all decision according the model setup and development were made by myself. Once the development of a model part was done, team meetings were conducted to pass the gathered knowledge to the team. In that way the team was able to do their own development according a proofed example. The work done was based on a sponsored simulation model of the stock 2019 Chevrolet Blazer which got expanded to be applicable for the selected architecture. Validation is based on the validation of the stock vehicle while relying on the valid development according set requirements of the added components.

4.1 Used Model Environment and Model Setup

4.1.1 Model Environment

The competition provided a Simulink model sponsored by MathWorks. It is used to show a feasible framework for starting the model development process. Simulink was chosen based on the sponsored model, former experience and because of its ability to accompany the whole MbD process from concept to actual control code while ensuring consistency and portability. I decided to establish a workflow which use the same model to go through MIL, SIL and HIL testing in an iterative manner. This approach was deemed to suit the team and was driven by the benefit of standardized controller software development. Such a linear but iterative process suits the team's challenge facing on-boarding of new members and developing new skills while participating in all test stages during one or more iterations [64].Additionally, assigned projects can be monitored along its made progress with respect to the MbD process. Below, the main benefits for using Simulink are listed. In the MIL testing stage available Simulink toolboxes are used to representing the HEV vehicle plant models. Additionally, the Simulink Requirement Editor is used to link set requirements to certain parts of the model, aiding documentation and evaluation. During SIL testing automated C-code generation and the real-time implementation library will be utilized. During HIL testing the strong connectivity with sponsored dSPACE products like ControlDesk, the MicroAutoBox II and the HIL emulator will be used.

4.1.2 Model Framework

The established model framework is done inside a Simulink Project. During the Simulink project initiation process, used models, model references, databases and environment variables are loaded and set up to ensure that all model parts are working together properly. During architecture and component selection model variants were used to test different components, architectures, and control strategies in the same model environment. Variants were controlled using programmable masks which switch between different setups. After the team's preferred architectures were found the model was reorganized to allow switching only between four defined options; the stock vehicle and three HEV architectures. The Matlab "Powertrain Blockset" is used to represent all propulsion system components and their connections. It offers predefined models for engines, motors, batteries, drivers, other electrical and drivetrain components and vehicles. One focus of this blockset is the two-way connections allowing a more functional representation of mechanical connections. With this connection block torque and speed signals allow information to be sent forward and backward between different components within the model architecture. This helps to reduce the number of visible feedback loops and simplifies the interactions between the front and rear powertrain components.

4.1.3 Model Overview

Based on the benefits of a blended model approach between functional and structural modeling methods this approach I decided to set up the model in this way. As far as applicable, the model is designed in a functional way to allow easy accessibility to new members. If block assumptions are not sufficient or not applicable, the team can develop its own equation-based models. The model is designed to follow an engine-to-wheel approach with forward-based calculations. The dynamic behavior of the vehicle and the powertrain is based on the driver's input and the dynamic feedback from the vehicle plant.

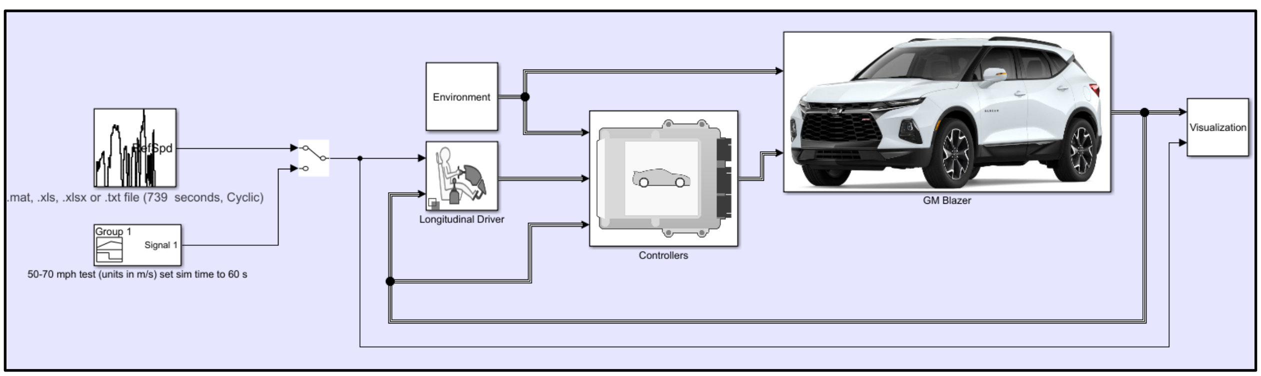


Figure 3: Top Level Model Structure

The top model consists of five major parts, namely the drive cycle source, the driver model block, the controller model, the vehicle plant model and the visualization block. Figure 3 visualizes the model structure from a top-level view. Dependencies in time can be seen by following the directions of the arrows. Drive cycle source data will be sent to the driver model and forwarded to the controller model. Both driver model and controller model are receiving vehicle feedback signals. The “Environment” block provides environmental parameters like temperature, pressure and road grade to the vehicle plant and the controller. In that way a feedback loop is created, where the drive cycle source block and the environment subsystem are serving as an input and the visualization block servers an output. Inside the feedback loop the driver sends pedal position signals to the controller model, which sends command signals to the according powertrain components. These signals are torque commands, gear commands, clutch commands and brake commands. Signals used for feedback are vehicle speed, clutch state, wheel speed and other component information. Figure 4 aims to visualize the signal processing within the top level of the model.

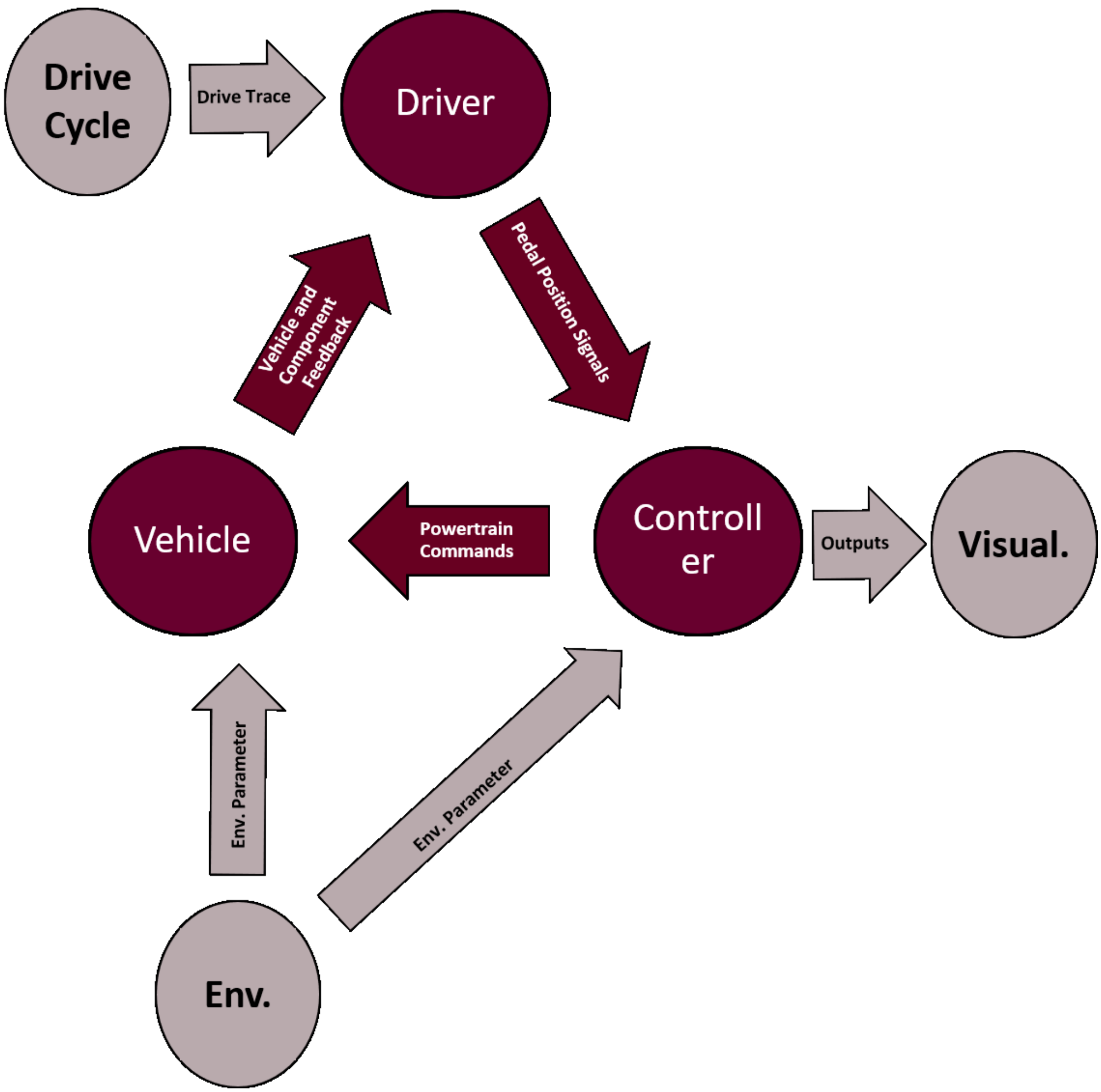


Figure 4: Signals in Top Level Model

4.2 Model Description and Development

Below a more detailed description of each model component will be given, including the used model approaches, the assumption made, and model parameters used.

4.2.1 Drive Cycle Source

The “Drive Cycle Source” block allows to load speed profiles into the model and map to an output signal. It includes all major drive cycle profiles and is able to implement custom drive cycles as “.mat”, “.xls”, “.xlsx” or “.txt” files. Additional it has a wide-open-throttle option allowing acceleration tests. The two received EMC drive cycles were converted into “.txt” files, which showed the fastest performance while initializing the model. While setting up automated testing procedures for performance and fuel economy requirement evaluation, this block was utilized due to its ability to load different drive cycle files from a script.

4.2.2 Driver Model

The driver model consists of the “Longitudinal Driver Model” and a switch enabling adaptive cruise control options. The control type is set to “Predictive” which mimics an optimal single-point preview depending on the vehicle mass and the coast down testing coefficients A, B and C [65]. Further driver characteristics can be set by adjusting the preview distance and the reaction time of the vehicle. Figure 5 summarizes the driver subsystem.

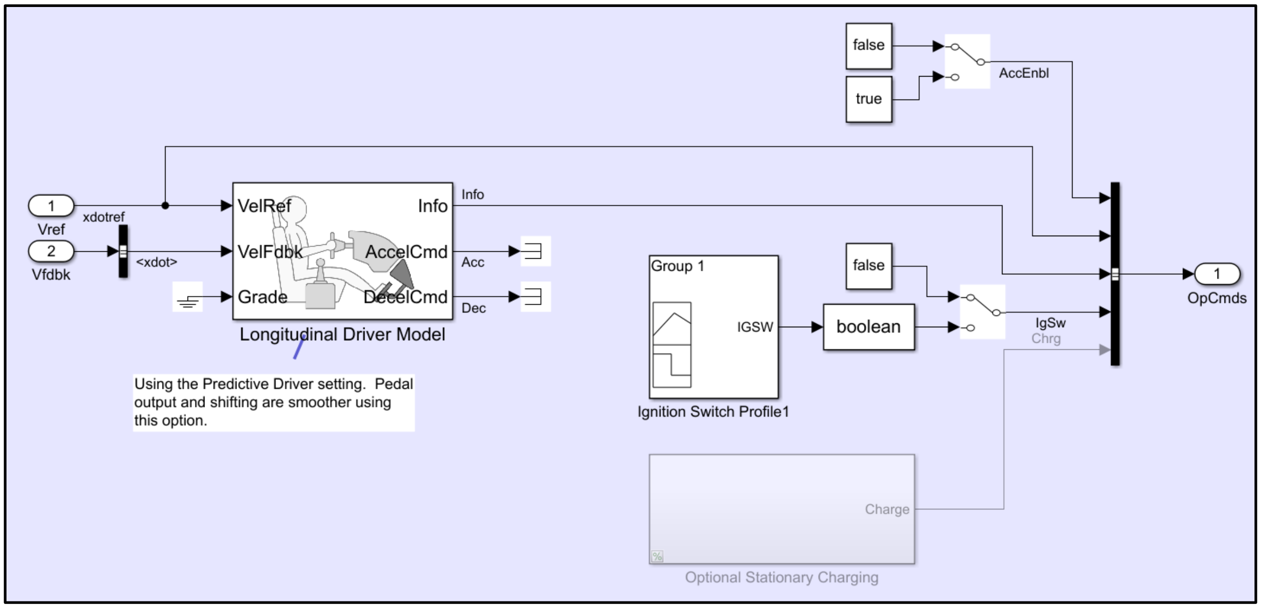


Figure 5: Overview Driver model

Two drivers were developed and used in the model. One driver shows the ability to follow the drive cycle profile accurately below an absolute speed error of 3 mph and an overall root-mean-square error of below 0.7. The other driver represents human driving behavior according to literature research [66]. Found preview distance and reaction time for both drivers are listed in Table 7 below. The distinction was necessary in order to receive accurate fuel economy numbers under laboratory test conditions and real-life driving behavior simultaneously.

Table 7: Drive Type Definition

Driver Type	Preview Distance [m]	Reaction Time [s]
Laboratory Test Driving	200	0.12
Human Driving	10	0.83

4.2.3 Environment

The Environment subsystem defines temperature, air pressure, grade and wind speed signals which will be used by certain components like the tires or engine. All parameters are set to constant values corresponding to normal conditions of 26.85 °C, the pressure is set at 101325 Pa and no wind. Those numbers are based on the initial set values from MathWorks. Grade constant can vary based on possible gradeability testing.

4.2.4 Controller Model

The controller subsystem takes several inputs from the driver model, the environment subsystem and vehicle feedback and outputs control signals to the vehicle plant model. It is structured in three layers, namely the Input Layer, the Output Layer, and the Application Layer. Input and Output Layer is used to either break out signals from a signal bus or create a signal bus by combining different signals. This layout was chosen to support MIL, SIL, and HIL testing because the input and output layers can be set up to be used for all testing stages while the application layer can be switched. This allows having different variants of the controller models. Inside the controller subsystem, the engine and transmission control modules, the hybrid supervisory controller and the ACC module can be found.

4.2.4.1 Hybrid Supervisory Controller

The HSC model consists out of 5 layers, namely Input Layer, Output Layer, Application Layer and additional two Conversion Layers used to convert signals from the Input Layer to the Application Layer and from the Application Layer to the Output Layer. All I/O are named according to their physical quantity and assigned SI unit. The Input Conversion Layer is used to convert input signals to useable signals for the Application Layer. For example, the conversion layer receives acceleration pedal position in percent from the input layer and outputs a wheel torque command in Newton meters to the application layer. The Output Conversion Layer is used to convert signals from the Application Layer to the correct format needed for the Output Layer as well as applying safety checks to not command unrealistic or dangerous values. Lastly, the Application Layer includes the HEV control strategy with all propulsion and braking modes. It is also responsible for controlling components and the correct interactions between them. Figure 6 shows the top-level structure in a simplified way.

Figure 6: HSC Structure Overview

The HSC uses Simulink and Stateflow blocks to represent the internal logic and organization. The HSC development will be explained in more detailed in Chapter 5.2.

4.2.4.2 Transmission Control Module

The transmission control module calculates gear shifting based on an upper and lower speed threshold defined based on the acceleration pedal position and the vehicle speed. If the speed exceeds or falls below one of the thresholds a gear shifting is commanded. It is realized by Stateflow logic in combination with upshift and downshift schedules. It was received as a sponsored model including needed shifting schedules from GM and therefore decided not to modify this model.

4.2.4.3 Engine Control Module

The engine control module consists of the "SI Controller" block including a predefined calibration corresponding to each powercube. Covered functionalities include engine control, start-stop logic, and active fuel management logic. The team received engine calibrations from GM and decided to not modify them at this point. Therefore, this block remains unchanged.

4.2.4.4 Adaptive Cruise Control Module

Once ACC is enabled by the driver pedal position signals generated by the ACC module are utilized to control the powertrain. This block is used by the CAVS subteam to test and modify developed ACC algorithms. Inside the driver model, ACC needs to be enabled. Once enabled the drive cycle works as a target vehicle, which the ACC algorithm tries to follow within a set distance.

4.2.5 Powertrain Model

The powertrain model is separated into three different subsystems, namely the engine model, the electrical plant and the drivetrain. It aims to represent any physical component inside the powertrain and the longitudinal vehicle dynamic behavior. Inputs to the powertrain model are signals related to the environment, engine feedback, vehicle feedback, and signals sent by the controllers. Outputs include the engine model, electrical plant model, and vehicle model feedback.

4.2.5.1 Engine Model

The engine subsystem is represented by the "Mapped SI Engine" block, a catalytic converter subsystem and additional belt losses applied through the BAS motor.

The engine model is based on sponsored model parameters. It allows vehicle level fuel economy and performance simulations and can be used for HIL engine control design. Model parameters and firing and non-firing engine data is provided and validated by GM based on actual engine test data. The implemented "Calibrate Maps" function allows to generate useable model maps from available test. The relative RMSE between generated maps and the raw test data varies between 1.8 and 3%. Based on these maps output engine torque is gathered based on a LUT with the inputs of the of the current commanded torque and engine speed. Afterwards the resulting engine torque and the engine speed will be used to gather the current air mass flow, fuel flow, exhaust temperature, and the brake-specific fuel consumption value based on LUTs. The engine model prioritizes to provide accurate engine outputs based on test data. A mathematical representation of implied engine dynamics is not sought. Therefore, the model outputs of the generated torque, the engine speed and the fuel flow are used. Torque and engine speed are necessary to determine drivetrain characteristics whereas the fuel flow will be used to calculate the equivalent fuel consumption of the vehicle.

Applied belt losses are assumed to be a constant 3 Nm multiplied by the belt ratio. Based on available data from Valeo, belt ratio is assumed to be 1 until more detailed belt design work is done. Table 8 summarizes belt system parameters. Belt losses will be subtracted from the generated engine torque. Based on the BAS motor being belted to the engine it was decided to add the belt losses in the engine subsystem to reflect its effect on the engine fuel efficiency as well as the fed forward engine subsystem torque.

The catalytic converter subsystem includes emission conversion efficiency based on the Air-Fuel ratio and the exhaust temperature calculated by the engine model. It is used to represent the engine emission before and after the catalytic converter. The engine subsystem structure can be seen in Figure 7.

Table 8: Belt System Parameters

Belt System Parameter	Value
Belt Losses	3 Nm
Belt Ratio	1

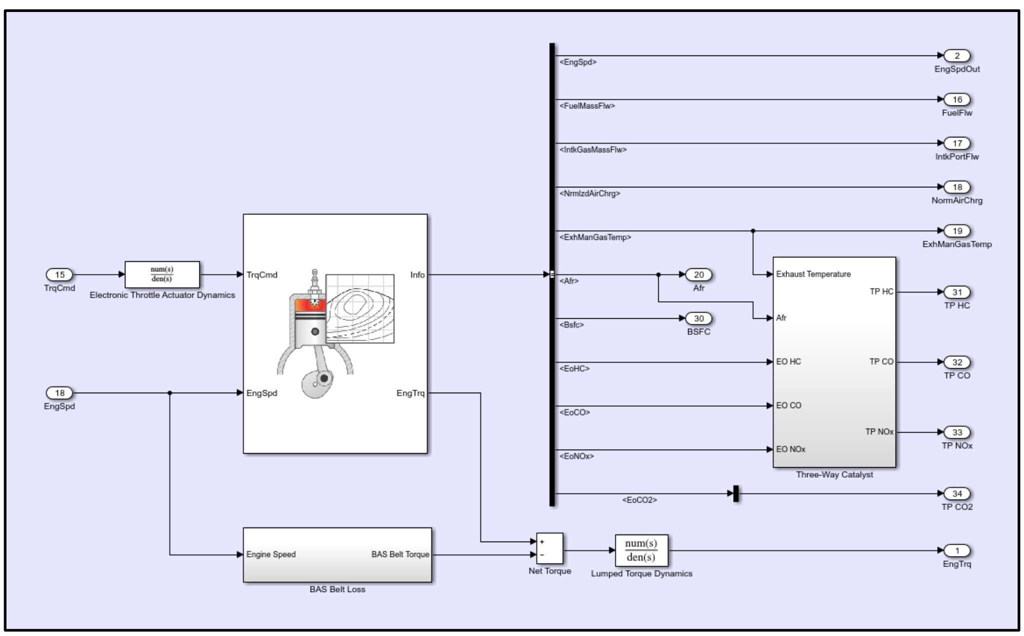


Figure 7: Engine model

4.2.5.2 Electrical Plant Model

The electrical plant consists out of the BAS motor, rear EM, HV battery pack and LV battery pack model as well as LV loads. Figure 8 shows the layout of the electrical plant and how they are connected.

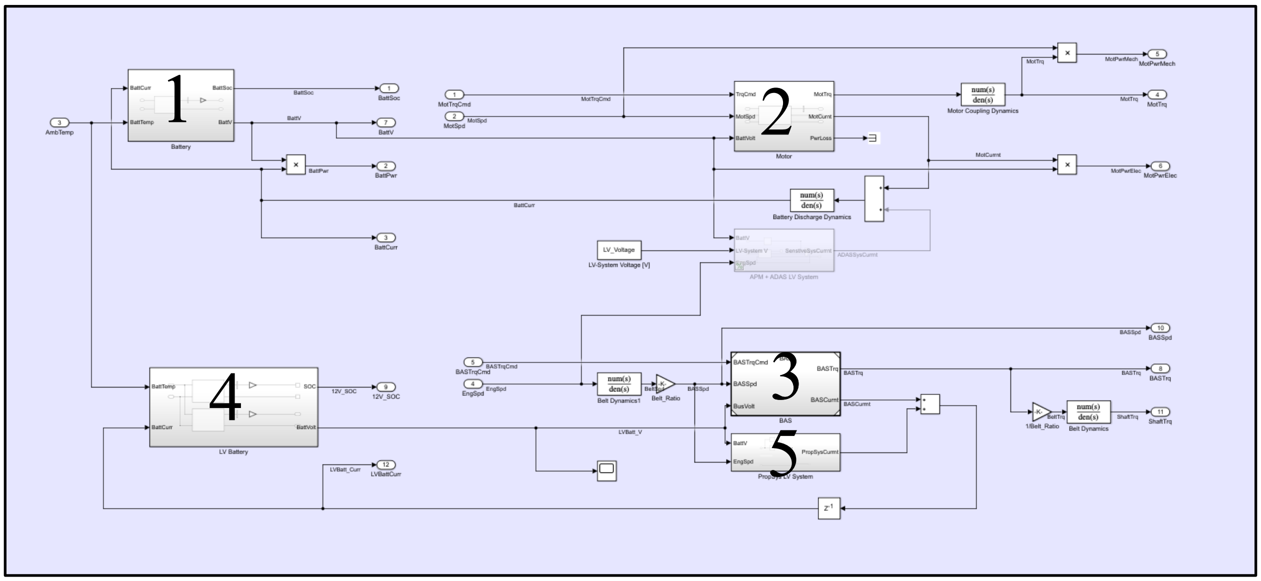


Figure 8: Electrical Plant Layout, 1) HV Battery Pack, 2) EM, 3) BAS, 4) LV Battery, 5) LV Loads

Rear motor and BAS motor Model

Starting with the rear EM a “Mapped Motor” block is utilized. Necessary parameters are a torque-speed envelope and an efficiency map. Both parameters were gathered throughout in-house testing of the YASA P400 during the EcoCAR3 competition and implemented in the model. Figure 9 shows the result of the efficiency tests for the YASA P400 for 300 V based on motor torque and speed

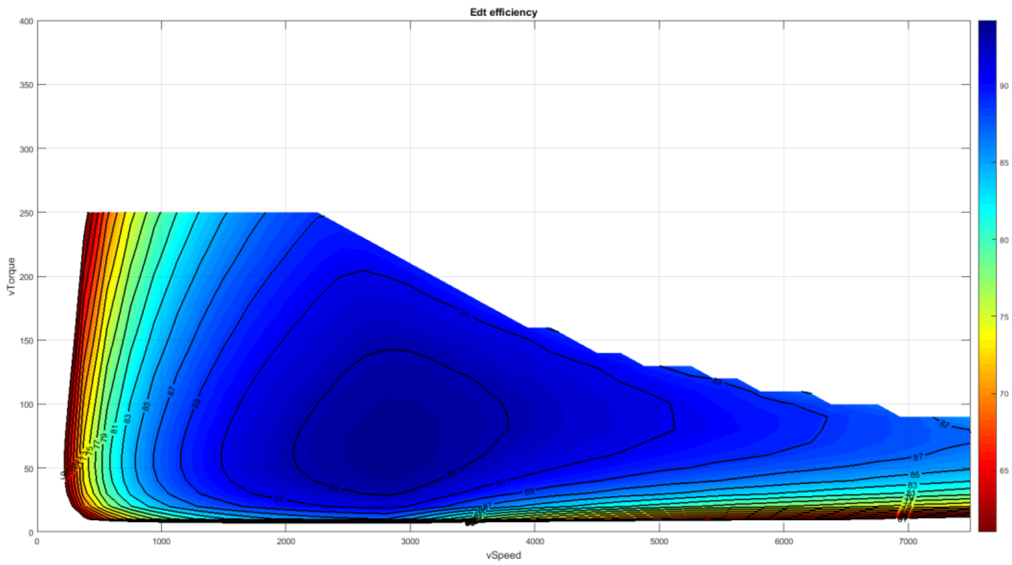


Figure 9: YASA P400 efficiency test data

The same motor model was used to model the BAS motor. In contrast to the YASA P400, the Valeo i-StARS system shows an asymmetrical power behavior. It can regenerate up to 4 kW but can only provide traction force up to 2.3 kW. Two separate “Mapped Motor” blocks were used to represent either generator or motor behavior. Based on the sign of the torque command the model switches between both blocks to use the correct behavior. Figure 10 shows how the BAS motor model looks in detail. Necessary model parameters for the BAS motor were found by a motor characterization tool developed by me. It approximates the torque-speed envelope and efficiency maps of a motor by using maximum power, maximum torque, maximum rpm and a generic efficiency map.

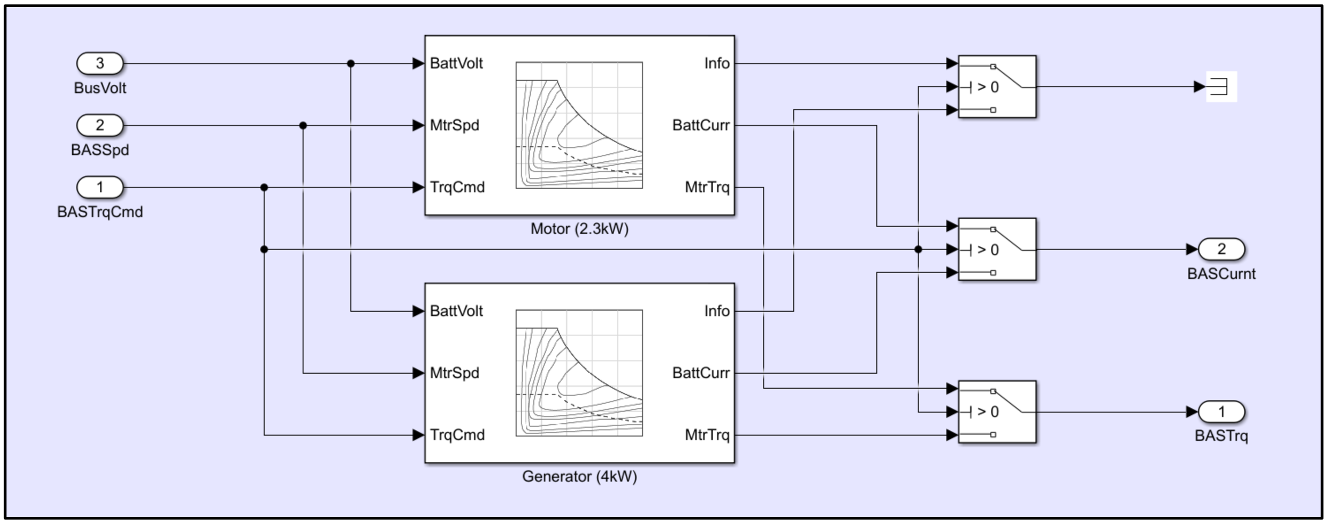


Figure 10: Detailed BAS motor Model

The mathematical representation of the motor calculating the battery current, I_{Batt}, based on the generated mechanical power divided by the product of the motor efficiency, η, and battery voltage, V_{Batt}. Equation 9 shows this calculation, where mechanical power is gathered by multiplying the motor speed, ω_{Mot}, and generated torque, $\mathrm{T}_{\mathrm{Mot}}$.

Equation 9: Battery current calculation

$$I_{Batt} = \frac{\mathrm{T}_{\mathrm{Mot}} * \omega_{\mathrm{Mot}}}{\eta(T_{Mot}, \omega_{\mathrm{Mot}}) * V_{Batt}} \qquad \text{(Equation 9)}$$

HV battery pack and LV battery Model

Two different equivalent circuit models were used for the HV and the LV batteries. The HV battery pack is represented by an OCV-SOC-R model included in the "Datasheet Battery" block. Model parameters including the OCV-SOC curve and the internal resistance are provided by

GM. It aims to represent the Lithium-Ion battery pack from the GM Malibu Hybrid. Based on the different cell chemistry of the LV battery, a model is needed which can represent a Lead-Acid battery pack sufficiently. Since the BAS motor will be used for engine cranking the model has to respond accurately to voltage drops during crank operation. Therefore, an OCV-SOC-R-RC model was chosen. Model parameters are set according to a comparable Lead-Acid investigated in current publications [67]. For both battery models temperature, dependencies are neglected. Gathered parameters are valid for room temperature set to 25°C.

Mathematical representation is of an equivalent circuit model is set around the calculation of the terminal voltage, V_T, based on the addition of the OCV, and the voltage drop over the internal resistance, V_0, and in the case of the LV battery over the first RC pair, V_1.

Equation 10: Terminal Voltage calculation

$$V_T = \mathrm{OCV(SOC)} - \mathrm{V}_0 - V_1$$

$$V_0 = \mathrm{I_{Batt}} * \mathrm{R}_0 \qquad \text{(Equation 10)}$$

$$V_1 = \int \frac{\mathrm{I_{Batt}}}{C_1} - \frac{\widetilde{V_1}}{R_1 * C\_1}\,\mathrm{dt}$$

Equation 10 shows the calculation of the terminal voltage where R_0 denotes the internal resistance, C_1 denotes the capacitance and R_1 denotes the resistance, $\widetilde{V_1}$ denotes the prior value of the voltage drop over the first RC pair. SOC calculation, as seen in Equation 11, is done according Coulomb counting approach, where Cap denotes the nominal capacity of the battery

Equation 11: SOC calculation

$$SOC = \frac{1}{\mathrm{Cap}} \int \mathrm{I}_{\mathrm{Batt}}\ \mathrm{dt} \qquad \text{(Equation 11)}$$

LV load Model

It was assumed that LV loads include loads caused by powering stock controllers, team-added controllers, team-built boards and the CAV system. Load values are set according to peak and continuous values and summarized in Table 9.

Table 9: LV Loads

System	Continuous Power	Peak Power
Engine Cranking	0 W	1800 W
Propulsion System (stock and team added)	250 W	400 W
CAVS	250 W	400 W

It is assumed that peak loads are occurring when the engine is started. Continuous values are reached once the engine has reached idle speed and above. A simple LUT is used to interpolate between peak and continuous values based on the engine speed, as to be seen in Figure 11. Based on the current voltage of the LV battery the load is used to calculate an applied current to the battery. Engine cranking is evaluated based on the model Start-Stop functionality.

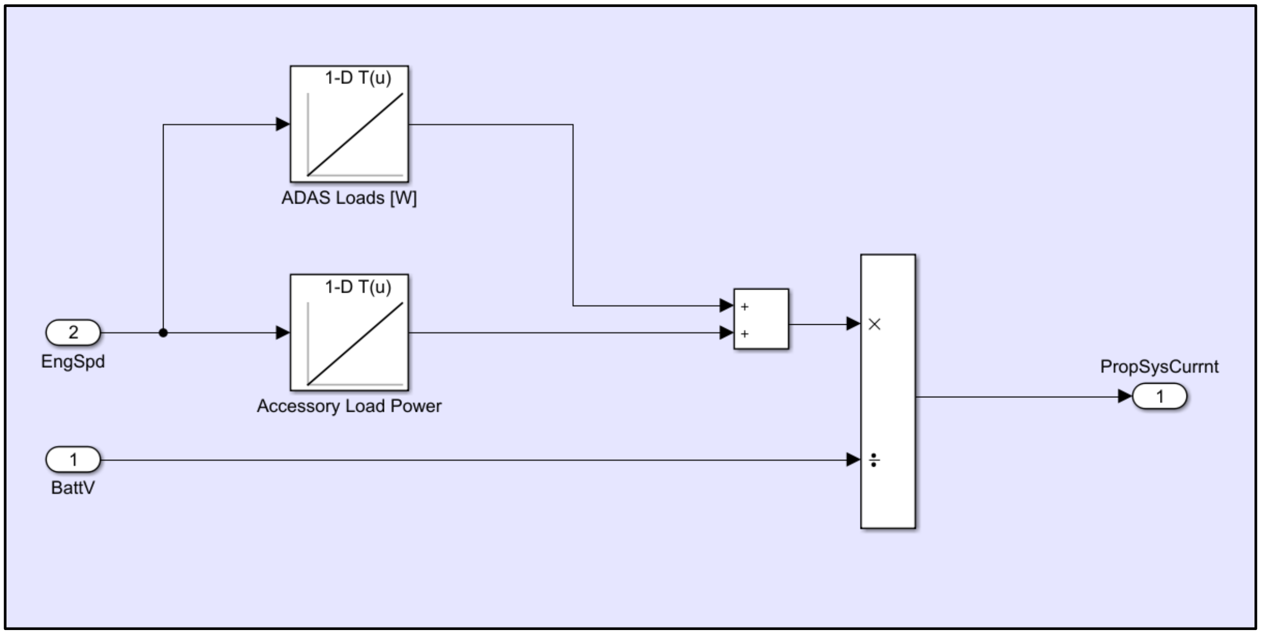


Figure 11: LV Load model

4.2.5.3 Drivetrain Model

The Drivetrain subsystem includes all mechanical components from the front and rear powertrain, the wheels and the vehicle chassis. The front powertrain includes a torque converter, a transmission, a front differential, connecting shafts and the front axle connected to the front wheels, brakes and the chassis. All model parameters of the front powertrain are stock components and model parameters are provided by GM and therefore will not be discussed in more detailed. The only change made is connecting the torque applied by the BAS motor to the engine shaft. The rear powertrain consists mainly of non-stock and team-built components and therefore had to be modeled in more detailed. Covered are all necessary shafts, the team-built gear reduction, the chosen clutch and the replaced differential. In that way, all necessary vehicle feedback will be gathered and sent to the according to parts of the model.

Shaft Model

Shafts are modeled with the “Two-Way Connection” and the “Torsional Compliance” block. The “Two-Way Connection” block allows sending torque and rotational speed signals forward and backward in the model. According to the chosen engine-to-wheel approach speed of components need to be sent as feedback to the previous component model. Using the “Two-Way Connection” block this feedback loop gets simplified achieving a more intuitive representation. Most of the “Powertrain Blockset” blocks have an option to use Two-Way connections to represent the powertrain in a more functional way. Figure 12 shows a simplified setup of the “Two-Way connection” and “Torsional Compliance block” representing an arbitrary shaft.

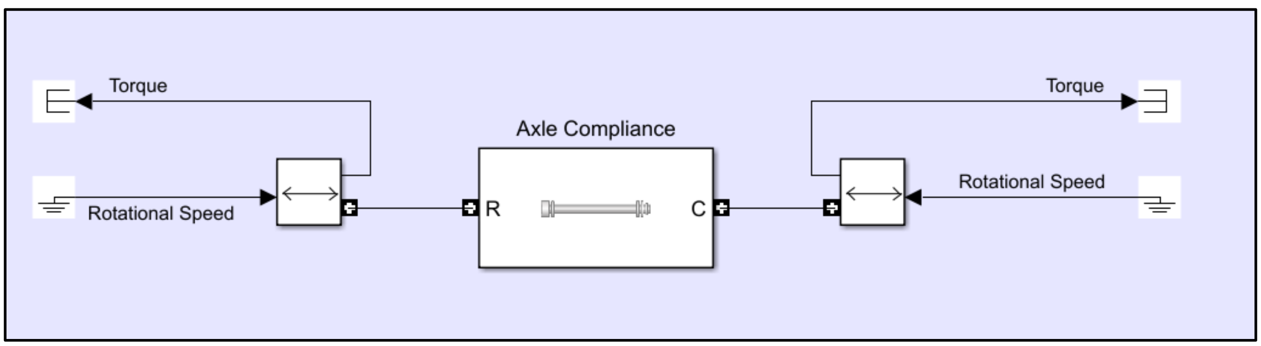


Figure 12: "Two-Way connection" and "Torsional Compliance" block

The “Torsional Compliance” block demands a torsional stiffness and torsional damping parameter. Preliminary analysis of the shaft design and material led to assumed values in Table 10. Those values were applied to all shafts in the rear powertrain. Calculated inertia values are added up to the closest components to account for the rear powertrain inertia. Preliminary shaft design received from the PropSys subteam was utilized to calculate inertia based on approximation of cylindrical segments. All shaft inertia values are summarized in

Table 11.

Table 10: Shaft Parameters

Shaft Parameter	Values
Torsional Stiffness	5000 Nm/rad
Torsional Damping	100 Nms/rad

Table 11: Rear Powertrain Inertia Values

Shaft Inertia Parameter	Values
Gearbox Input Shaft	0.0004 kg*m^2
Gearbox Output Shaft	0.0005 kg*m^2
Driveshaft	0.0006 kg*m^2
Half Shafts	0.0005 kg*m^2

In implementation, the shaft model is represented by torsional parallel damper spring system. Equation 12 describe the calculation of this system where ω_1 and ω_2 denote the input and output shaft speed, $\widetilde{\omega}_1$ and $\widetilde{\omega}_2$ denote the prior state of those parameters, as well as k denotes the torsional stiffness, b denotes the torsional damping and T_1 and T_2 denote the input and output torque.

Equation 12: Rotational Damper-Spring System

$$(\omega_1 - \omega_2) * k + \int (\widetilde{\omega}_1 - \widetilde{\omega}_2)\, dt * b = \mathrm{T}_1 = -T_2 \qquad \text{(Equation 12)}$$

This information is passed through the earlier mentione “Two-Way Connections” to be used in the components connected to the shaft like for example the gear reduction or clutch model

Gear Reduction Model

The team-built gear reduction is represented by the “Gearbox” block. Necessary parameters are the gear ratio, inertia of input and output shaft as well as input and output shaft damping. The gear ratio was found to be 1.6 with fuel economy optimization of the control strategy over both provided drive cycles. Input shaft inertia is calculated as the inertia of the shaft added up with the inertia of the EM found in the datasheet. Output shaft inertia is just the calculated inertia from preliminary shaft design. Damping values for both shafts are set to be low to represent the shaft bearings and the decreased vibrations through that. Table 12 shows all used parameters

Table 12: Gear Reduction parameter

Gear Reduction Parameter	Values
Ratio	1.6
Input Shaft Damping	0.001 Nms/rad
Output Shaft Damping	0.001 Nms/rad
Input Shaft Inertia + EM Inertia	0.0004 kg*m^2 + 0.083 kg*m^2 = 0.0834 kg*m^2
Output Shaft Inertia	0.0005 kg*m^2

Transmission dynamics are represented, similar to the shaft model by speed and torque on each end of the component. Equation 12 represent component behavior taking into account the damping value, b, as well as the inertia value, J, of both inputs and N denotes the gear reduction ratio.

Equation 13: Dynamic model of the gear reduction

$$(\omega_1 * N * b_1 - \omega_2 * b_2) + \int (\tilde{\omega}_1 * N * J_1 - \tilde{\omega}_2 * J_2)\, dt = \mathrm{T}_1 = -T_2 * N \quad \text{(Equation 12)}$$

Clutch Model

The modeled clutch is the Tilton 5.5" OT-III Metallic Racing Clutch with two-plate configurations and orange springs. The used "Disc Clutch" block demands the net force equivalent net radius, effective applied pressure area, engagement pressure threshold, shaft inertias, friction coefficients, damping and actuation time constant. Most of these parameters were not available. A decision was made to stick with the initial values defined by MathWorks until more accurate parameters are available. In that way, functionality was ensured while model accuracy can be improved in the future.

In implementation two different states of the clutch needs to be considered; clutch open and clutch closed. Both states need to have a dynamic model and a friction model both are summarized in the following equations where $\mathrm{N_{disc}}$ denotes the number of discs inside the clutch, P_c denotes the applied pressure, A_{eff} denotes the effective area, R_{eff} denotes the effective clutch radius, and μ denotes the friction coefficient.

Equation 14: Unlocked State

$$(\omega_1 * b_1) + \int (\tilde{\omega}_1 * J_1)\, dt \ + \mathrm{T}_f \ = \ \mathrm{T}_1$$

$$(\omega_2 * b_2) + \int (\tilde{\omega}_2 * J_2)\, dt \ + \mathrm{T}_f \ = \ T_2$$

(Equation 14)

$$\mathrm{T}_f \ = \ \mathrm{N_{disc}} * P_c * A_{eff} * R_{eff} * \mu * \tanh(4((\omega_1 - (\omega_2))$$

Equation 15: Locked State

$$(\omega_1 * b_1 - \omega_2 * b_2) + \int (\tilde{\omega}_1 * J_1 - \tilde{\omega}_2 * J_2)\, dt = \mathrm{T}_1 = T_2 \qquad \text{(Equation 15)}$$

Differential Model

The modeled differential is the stock 2016 Chevrolet Camaro rear differential with a ratio of 2.77:1. Inertia values were calculated based on the existing CAD drawing. Damping values are assumed to be low based on the bearing situation. Table 13 summarizes used model parameters.

Table 13: Differential Parameters

Shaft Inertia Parameter	Values
Ratio	2.77
Damping parameters	0.001 rad/s
Carrier Inertia	0.025 kg*m^2
Axle 1 (Halfshaft) Inertia	0.0005 kg*m^2
Axle 2 (Halfshaft) Inertia	0.0005 kg*m^2

The mathematical representation follows a similar approach than the gear reduction approach. Similar mechanical constraints can be seen in using the inertia. damping and ratio values. Difference is the torque distribution assuming that the input torque, T_3, will be split in two outputs where each output torque, $\mathrm{T}_{1,2}$, is half of the input torque. Equation 16 shows the dynamic model of differential.

Equation 16: Dynamic model of differential

$$(\omega_{1,2} * N * b_{1,2} - \omega_3 * b_3) + \int \left(\widetilde{\omega}_{1,2} * N * J_{1,2} - \widetilde{\omega}_3 * J_3\right) dt$$
$$= 0.5 * \mathrm{T}_{1,2} = -T_3 * N \qquad \text{(Equation 16)}$$

Wheels, Brakes and Chassis Model

Wheel, Brakes and Chassis model parameters are provided by GM and are confidential. Therefore, only functionality will be discussed. The Longitudinal Wheel block is used to represent front and rear wheels with the associated brakes. Calculated front and rear axle force will be sent to the “Vehicle Body 1DOF Longitudinal” block. This block calculates resulting vehicle speed and vertical forces on both axles. Vertical forces will be sent back to the wheels to calculate the resulting forces on the wheels in a feedback loop. The chassis model takes into account grade, aerodynamic drag, and general vehicle losses.

The wheels and brakes are represented together in one model. Rotational wheel dynamics are calculated based on the summation of all applied torques where T_{i} denotes the combined input torque, $\mathrm{T_{Axle}}$ denotes the applied axle torque, T_{Brake} the applied brake torque and T_d denotes the arising tire torque.

Equation 17: Wheel torque summation

$$\mathrm{T_i} = \mathrm{T_{Axle}} + T_{Brake} + T_d$$

$$\mathrm{T}_{Brake} = \frac{\mu * \mathrm{P} * \pi * B_a^2 * R_m * N_{pads}}{4} \qquad \text{(Equation 17)}$$

$$T_d = \int \frac{\omega * R_e}{L_e + \omega * R_e} * \left(F_x * R_e + M_y\right) dt$$

In Equation 17 μ denotes the friction coefficient, P denotes the applied pressure, B_a denotes the brake actuator bore diameter, R_m denotes the mean radius of the brake pads, N_{pads} denotes the number of pads, R_e denotes the effective tire radius, L_e denotes the tire relaxation length, F_x denotes the longitudinal force developed by the tire and M_y denotes the rolling resistance torque. Tire force, F_x, is calculated by the magic formula with constant values representing stiffness, B, shape, C, peak, D, and curvature, E, as seen in Equation 18 below.

Equation 18: Wheel force calculation

$$F_x = F_z * D * sin(C * tan^{-1}((B * k - E(B * k - tan^{-1}(B * k))) \qquad \text{(Equation 18)}$$

The chassis representation uses the tire force, F_x, to calculate the vehicle speed and the resulting vertical forces needed to calculate the tire forces. Equation 19 and Equation 20 show how the chassis dynamics are calculated, where V denotes the vehicle speed, F_d denotes the aerodynamic drag forces, $C_d$denotes the drag coefficient, ρ denotes the air density, A the frontal area, V_{wind} denotes the wind speed, m denotes the vehicle mass, h denotes the height of the CoG above the ground, g denotes the gravitational acceleration, γ denotes the angle of the road inclination, L_f denotes the distance between the front axle and the Cog, and L_r denotes the distance between the rear axle and the CoG.

Equation 19: Vehicle chassis dynamics

$$V = \int \frac{\left(2 * F_{xf} + 2 * F_{xr}\right) - F_d}{m} dt$$

(Equation 19)

$$F_d = 0.5 * C_d * \rho * A \left(\tilde{V} \ + \ V_{wind}\right)^2$$

Equation 20: Vertical wheel force

$$F_{zf} = \frac{+h\left(F_d + m * g * \sin(\gamma) + m\dot{V}\right) + L_f * m * g * \cos(\gamma)}{N_f * (L_f + L_r)}$$

(Equation 20)

$$F_{zr} = \frac{-h\left(F_d + m * g * \sin(\gamma) + m\dot{V}\right) + L_r * m * g * \cos(\gamma)}{N_r * (L_f + L_r)}$$

4.2.6 Visualization

The Visualization subsystem is used to calculate fuel economy, plot necessary signals and save signal values into the base workspace of Matlab for postprocessing data and automated testing. Utilized were "Scope" and "To Workspace" blocks. Fuel economy calculation happens by converting used battery power to an equivalent fuel flow with a competition defined conversion factor of 32.3 and the fuel density. Afterwards the equivalent fuel flow will be used to calculate the equivalent mpg. Equivalent fuel consumption happens according to Equation 21 where FC_{eqv} denotes the equivalent fuel consumption, $\dot{m}_{fuel}$ denotes the fuel mass flow, P_{Batt} denotes the used battery power and ρ_{fuel} denotes the fuel density.

Equation 21: Equivalent fuel consumption

$$FC_{eqv} = \int \dot{m}_{fuel} + P_{Batt} * 32.3 * \rho_{fuel} \, dt \qquad \text{(Equation 21)}$$

4.3 Model Confidence

It is important to validate the confidence of each developed model to gain an insight into the fidelity, accuracy and reliability of the gathered results. An attempt was made to evaluate model confidence with a modified project management tool called Process Failure Mode and Effect Analysis (PFMEA). In that way each model and subsystem can be evaluated against its implicit risk of failure, which is an inverse relationship to its model confidence. The PFMEA was set up by summarizing explanations of implemented model functionality, made assumptions, available validation methods, occurring mechanism of failure, the potential impact of failure and remedy performance. Based on these factors' severity, occurrence and detection rating is assigned.

Ratings are ranking between 1 – 10. The product of all three ratings is the risk priority number (RPN), where a higher RPN correlates with a low level of confidence. In case of an RPN exceeding a certain threshold, mitigation actions have to be done to lower the RPN and therefore increasing the model confidence. This was done for all model components and functionalities. Table 14 shows an example of the BAS motor model confidence. In that way, a detailed model description is gathered describing how the model works and where improvements can be done.

Table 14: PFMEA Example

#	Item	Function	Potential Failure Mode	Potential Impact	Detection	Remedy Perf.	Severity	Occurrence	Detection	RPN
6	12V Valeo BAS	Representing the Valeo BAS based on mapped data from Valeo.	Use of corrupted data Insufficient model approach	LV system and Engine would operate inaccurately	Checking team-defined model requirements (BAS requirements).	Contact Valeo, acquire more accurate parameter	3	4	4	48

As seen in Table 14, the PFEMA was done for all modeled components. Mitigation plans were set for the highest risk components, which were considered to be the rear powertrain model due to its low model accuracy and the HSC model due to its high complexity and impact. Mitigation involve acquiring more accurate model parameter for the rear powertrain model and starting excessive SIL testing for the HSC model as soon as possible.

Table 15: Model Confidence by Component

Item	Engine	Malibu Pack	YASA Motor	Valeo BAS	LV Battery	LV Loads	Transmission	Rear Powertrain	Vehicle	ECM	TCM	HSC
RPN	84	30	15	48	75	105	84	168	105	84	84	135

4.4 Model Validation

Validation of the stock vehicle fuel economy is done over official EPA certificated fuel economy results for the HWFET and UDDS drive cycles and unofficial US06 city and highway fuel economy data. Fuel economy estimation for the unofficial data is done by comparing a different Chevrolet Blazer model. Changes for the used gasoline type and the estimated vehicle efficiency of the stock vehicle were considered. Until official fuel economy data for all drive cycles needed is available this information has to stay confidential. Based on the validated stock vehicle model validation for the changed architecture is assumed based on the validation of the added and removed components in comparison to the stock vehicle.

4.5 Summary

The vehicle model was set up in Simulink allowing to use the same model through all testing stages. Models were developed representing the driver, all controllers and the vehicle with all necessary powertrain components. Explanations were given including the used model parameters, used model assumptions and the assigned model confidence. In detail, two driver models, the HSC controller model, the rear powertrain model, the electrical plant model and the BAS motor model was developed. Each developed model was evaluated against its model confidence and improvements are done to the highest risk components. This was done to lower its assigned RPN and increasing the overall model confidence.

5 Control System Development

The design of the control system in year 1 focuses on the controller hardware selection and integration, establishing communication between all controllers, the design of the hybrid supervisory controller software and the design of the implemented control strategy. Goals were to ensure simplicity, functionality and the team's ability to design their own boards from concept to the finished product. A lack of experience inside the team caused myself to come up with necessary design principals for the control system and the HSC software architecture implemented given limitations through the components and the competition. The developed serial data network architecture is based on those principals and was developed by me. Additional training was provided to the team. This was important to teach the thought process behind made decision for future years, allowing the team to modify it once issues will occur.

5.1 Serial Data Network Architecture

Figure 13 shows the developed serial data network architecture including all stock, team-added and team-built controllers from the CSMS and CAVS side. Colored lines represent Controller Area Network (CAN) lines. Overall six CAN lines are used where three lines are stock GM CAN, namely the HS GMLAN, Gateway Expansion LAN, and GM Chassis LAN with a transmission rate of 500 kb/s. Additionally three lines are added, namely the HS PropSys LAN, HS Batt LAN and the CAN_CAVS_HSC LAN with a transmission rate of 500 kb/s. All CAN lines are tapped into the HSC. Further all lines, except the CAN_CAVS_HSC LAN will be terminated in the stock gateway module. Components which are not able to communicate via

CAN will be collected in the team-built Front Control Module (FCM) and Rear Control Module (RCM).

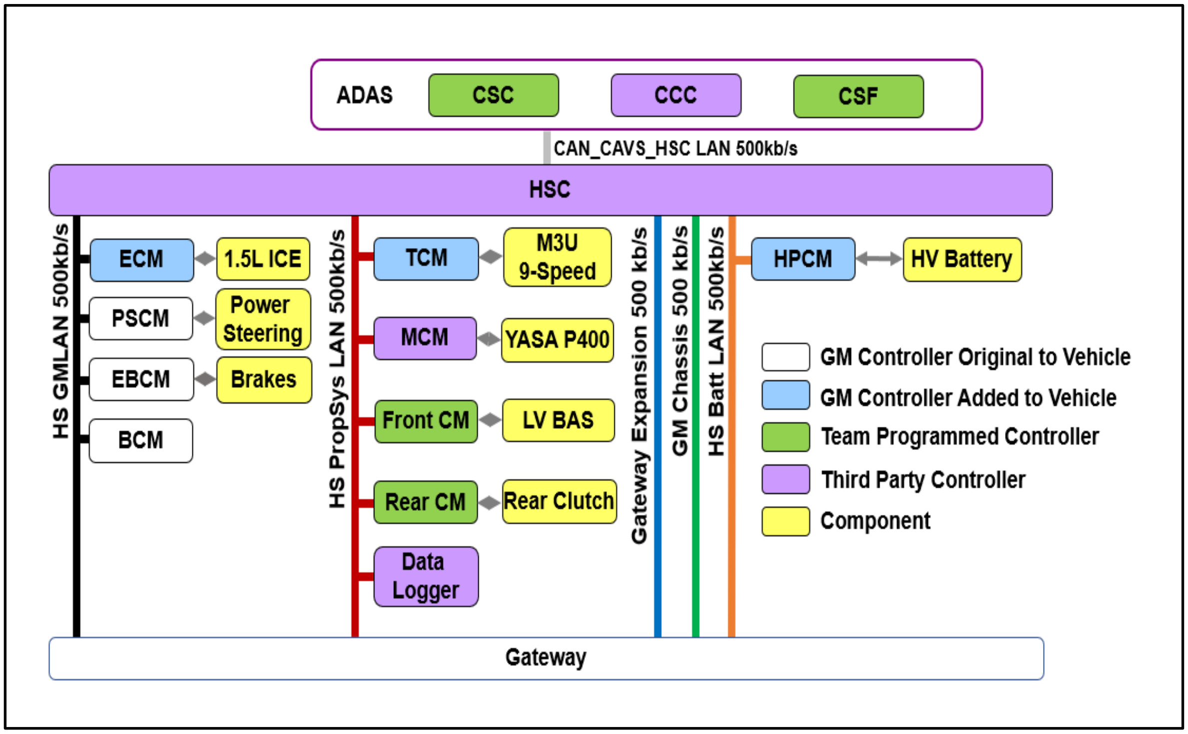


Figure 13: Serial Data Network Architecture Diagram

5.1.1 HS GMLAN

The HS GMLAN is the main communication line of the stock serial data network architecture including the Power Steering Control Module (PSCM), Electronic Brake Control Module (EBCM), and Body Control Module (BCM). The Engine Control Module (ECM) will be replaced with the provided ECM for the 1.5L GM Engine. No further modifications will be done to this line.

5.1.2 HS PropSys LAN

This line is primarily used to collect data from the team-added and team-built components, which is the rear powertrain and the two control modules. Additionally, the Transmission Control Module (TCM) needed to be placed on this line to separate the ECM and TCM. The provided engine and transmission controller needed to be separate to allow communications between the ECM and TCM over the HSC. This needs to be ensured to make modifications to control signals with the HSC. A data logger is placed on this line with access to the Gateway Module to log CAN messages used for diagnostics, debugging and error evaluation.

5.1.3 Gateway Expansion & GM Chassis LAN

These lines have two distinct purposes. First, they will be used to have a distinct line for CAN messages needed from the Gateway Module. The Gateway Module will receive almost all CAN message necessary inside the car. It was decided that a dedicated line would be useful to support the CAVS with necessary signals. Secondly both lines can be used as back-up lines, in case of critical bus overload at one of the other lines. This decision was made early to be considered during the harness building process.

5.1.4 HS Batt LAN

Due to the assumed high load of CAN messages the HS Batt Lan contains only the Hybrid Powertrain Control Module (HPCM) which is the Battery System Manager (BSM). It is used to control the sponsored GM Malibu Battery Pack.

5.1.5 CAN_CAVS_HSC LAN

This line connects the HSC and the CAVS Safety Controller. It ensures connectivity between the Control System and CAVS.

5.1.6 Serial Data Network Architecture Components

All used components are summarized in Table 16. Starting with the HSC, the dSPACE MicroAutoBox II was chosen because of its compatibly with other dSPACE products like ControlDesk and Matlab/Simulink. This allows the development of all Electronic Control Units (ECUs) in Matlab/Simulink as well as testing them in a SIL/HIL environment. Additionally, the MicroAutoBox II was provided by dSPACE for the EMC. The team developed boards will be used to control power electronics cooling systems, control the BAS motor, control the rear clutch actuator, will include the power electronic fusing, and initialize vehicle wake up procedures. Beside that, the main rear powertrain control is the Rinehart Motion Systems Motor Control Module (MCM). The Rinehart MCM was chosen because the motor pairing from EcoCAR3 is available and the team has former experience with this component. For the engine, transmission and battery pack the associated controller provided by GM will be used. The CAVS consist out of the CAVS Computational Controller, CAVS Safety Controller and the CAVS Sensor Fusion Board. Utilized will be the Intel Tank for the CAVS Computational Controller and again team-built designs for the other two CAVS controllers. All other controllers will remain unmodified and therefore will be the stock components.

Table 16: Control Components

Controller	Supplier	Description
HSC	dSPACE	Hybrid Supervisory Control. Team has input on software/calibrations on the controller. The sponsored MicroAutoBox II will be used.
PSCM	GM	Power Steering Control Module. Team has no input on the software/calibrations on the controller.
EBCM	GM	Electronic Brake Control Module. Team has no input on the software/calibrations on the controller.
BCM	GM	Body Control Module. Team has no input on the software/calibrations on the controller.
MCM	Rinehart Motion Systems	Motor Control Module. Team has input on inverter calibrations during pairing process. Motor/Inverter Pairing: Rinehart mapped the inverter according to YASA P400 motor.
FCM	Team built	Front Control Module. Team has input on software/calibrations on the controller. Used for power electronics cooling systems, BAS commands from HSC
RCM	Team built	Rear Control Module. Team has input on software/calibrations on the controller. Manage the rear clutch control, power electronics fusing, and vehicle wake up procedure
HPCM / BSM	GM	Hybrid Powertrain Control Module / Battery System Manager. Team has no input on the software/calibrations on the controller.
CSF	Team built	CAVs Sensor Fusion. Team has input on software/calibrations on the controller. All front sensor data will be fused there.
CCC	Intel	CAVs Computation Controller. Intel Tank
CSC	Team Built	CAVs Safety Controller. Team has input on software/calibrations on the controller.
ECM	GM	Engine Control Module (For LYX 1.5L Turbocharged Engine). Team has no input on the software/calibrations on the controller.
TCM	GM	Transmission Control Module (For M3U 9-Gear Transmission). Team has no input on the software/calibrations on the controller.

5.2 Hybrid Supervisory Controller Software

The HSC will act as the main source for controlling the vehicle. It includes diagnostic and fault mitigation modules, energy management algorithms, start-up and shutdown procedures, component control rings and output safety checks. Figure 14, Figure 15 and Figure 16 summarize the overall HSC software structure. Currently the implemented structure is focused on functionality. The team is working on implementing a software structure including more detailed safety, diagnostic and fault mitigation modules. Nevertheless, these blocks are implemented with basic functionality. In a first iteration diagnostic and fault mitigation modules for pedal position processing were developed on a HIL testbench by a dedicated team member.

5.2.1 Layers

The developed software structure consists of five layers, namely the Input layer, the Input conversion layer, the Application layer, the Output Conversion layer and the Output layer. This was necessary to organize the information flow through the main controller of the vehicle.

5.2.1.1 Input and Input Conversion Layer

The Input layer will be used to decode necessary CAN messages and collect all inputs from digital, analog and serial sources. It will receive inputs from the keyless sensor, an external drive mode switch, the PRNDL stick and all connected controllers. All needed signals and messages will then be sent forward to the Input Conversion Layer. The Input Conversion Layer's main purpose is to convert all available signals from the input layer to useable signals for the application layer. Further simplified diagnostics and fault mitigation modules are implemented establishing and ensuing valid communication between controller to controller and controller to sensors.

5.2.1.2 Application Layer

The Application Layer consists of the HSC Main Ring and the Operation Mode Loop. The HSC Main Ring starts with switching from Standby to Wake Up once the driver approaches the car. The Keyless sensor on the BCM will detect the key and send a signal to wake up the ECM and TCM. This signal will be recognized by the RCM, which sends a WAKE signal to the HSC. It initiates the Wake Up procedure and therefore will establish proper communication with all team added controllers. Once the Engine Start button is pressed Start Up procedure will begin. It observes engine and rear powertrain start up. Once all components are ready to operate the HSC Main Ring will switch into Drive Ready, which allows the Operation Mode Loop to be started. Once the engine start button is pressed again shutdown procedures will be started including engine shutdown and rear powertrain shutdown. This includes a bus bleeding process needed to ensure an HV drain. Once the driver exits the car and the key cannot be detected anymore the vehicle turns into Standby mode ready to be started again.

As said before once Drive Ready state is reached the Operation Mode Loop can be used to propel or brake the vehicle. Based on the torque request either brake modes or propulsion modes are used. The Propulsion modes will be chosen by an external switch. Available options are EV Mode, ICE Mode, HEV Mode and HEV Performance Mode. Main propulsion mode will be HEV Mode. HEV Performance Mode will have the same functionalities as HEV Mode but different calibrations, focused on performance rather than fuel economy. EV and ICE Mode will not be used in normal operation. More likely these modes will be used to educate new team members on a simplified system. Implemented Brake Modes are Blended Braking, which incorporates a parallel regenerative braking approach and Mechanical Braking used for emergency braking situations. Outputs of the Operation Mode Loop will be power commands and speed values of the BAS, EM and ICE, component states of the rear clutch and the transmission and brake pressure commands for the disk brakes. Those signals will be sent forward to the Output Conversion Layer.

5.2.1.3 Output Conversion and Output Layer

The Output Conversion Layer uses all signals from the Application Layer and ensures the operation of each component within its limitations. Received power signals will be used to calculate torque commands for the BAS and the EM. Engine Torque Request and Brake Pressure Request will be converted into modified pedal position signals used by the ECM, TCM and EBCM. Lastly, the Output Layer converts the signals into the correct format, packing CAN messages and creating digital or analog signals as necessary.

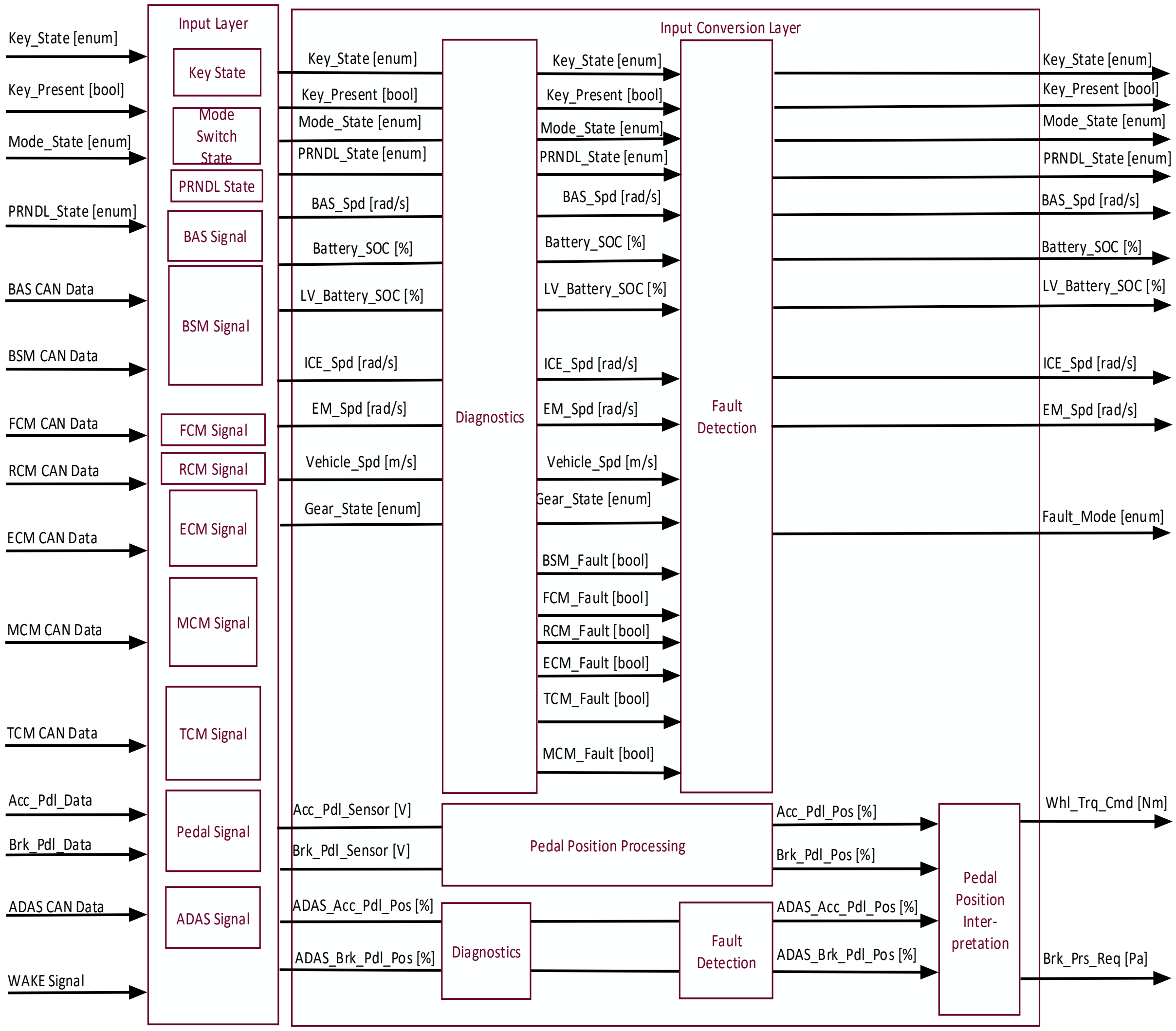


Figure 14: Input and Input Conversion Layer

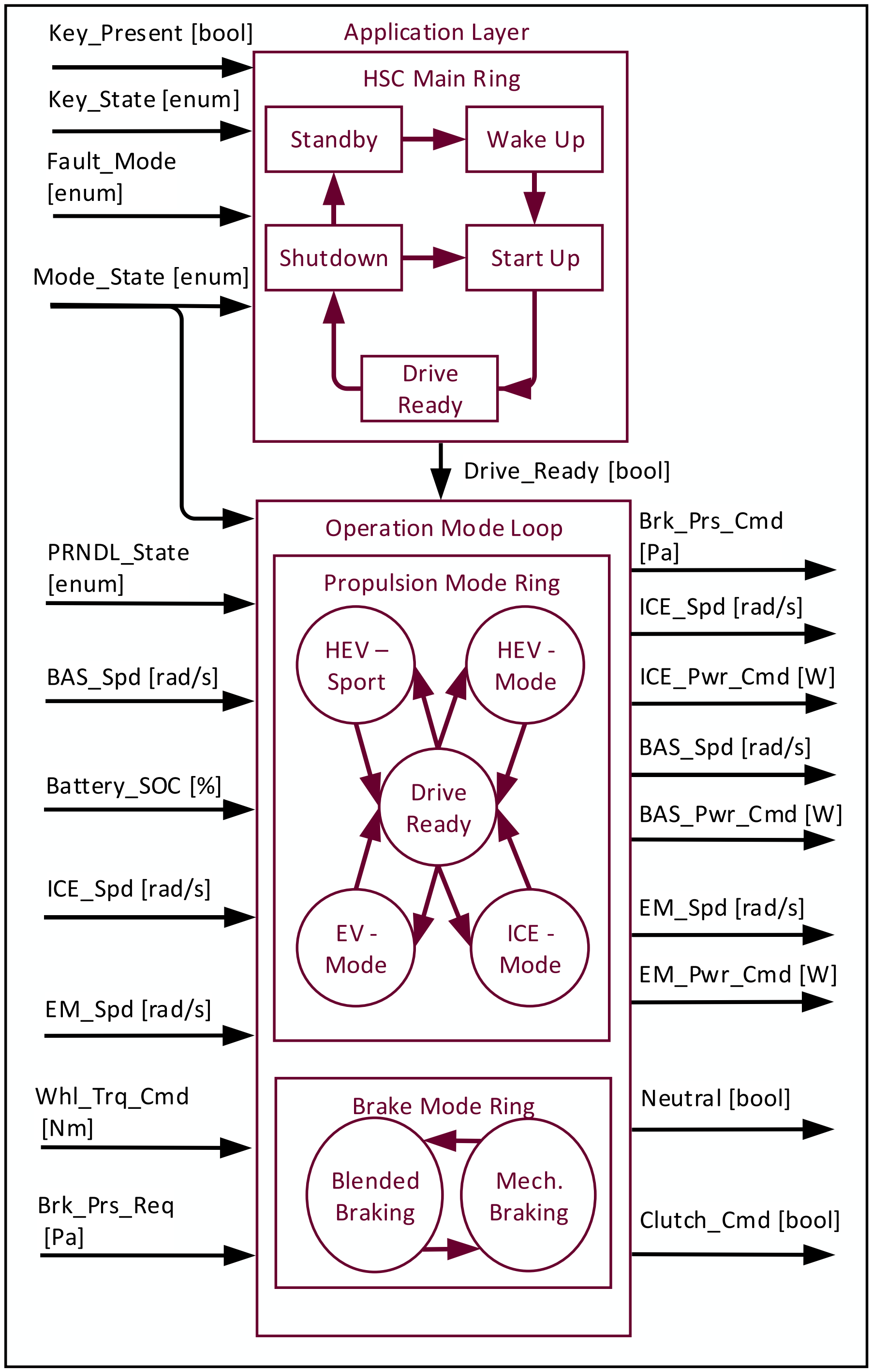


Figure 15: Application Layer

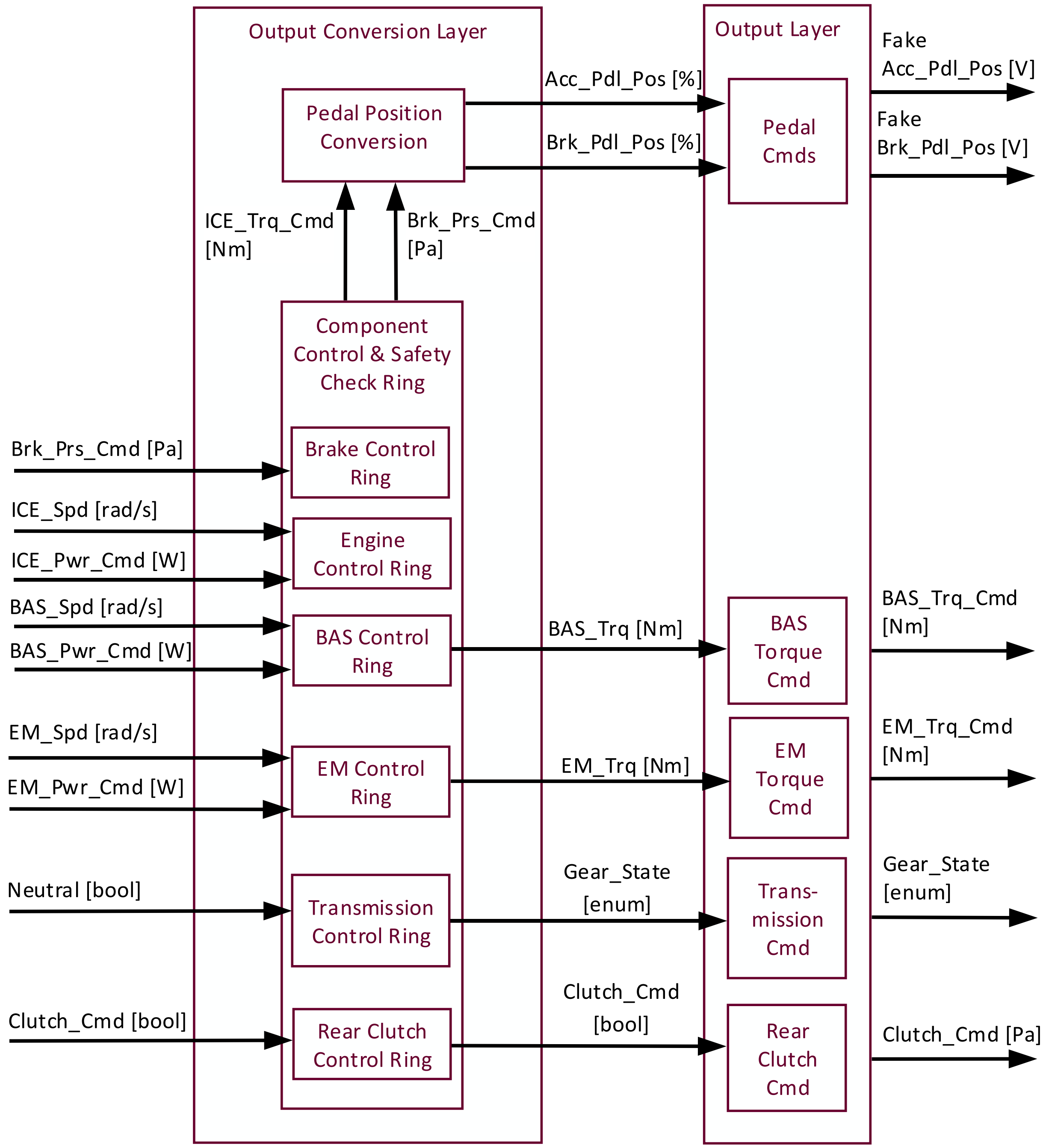


Figure 16: Output Conversion and Output Layer

5.3 Summary

The developed control system is focused on establishing proper and understandable communication between all used controllers. One of the main issue was to allow communication between team-added, team-built, stock GM and external added GM controllers. Therefore, CAN is utilized as much as possible allowing a standardized communication between all controllers. The team-built boards will act as a gateway between additional controllers not able to communicate via CAN like the clutch controller. The HSC software structure was set up to centralize necessary calculation for operating the powertrain. A five layer structure was chosen. The main layer is the application layer consist out of the HSC Main Ring and the Operation Mode Loop. The HSC Main ring ensures proper Start up and Shutdown procedures, where as the Operation Mode Loop determines powertrain component signals. In parallel an ICE, EM and BAS motor control ring was set up to ensure proper operation of this components. At this point the HSC software structure focuses on functionality. However, first attempts are made to incorporate system safety, diagnostic and fault mitigation into it.

6 Control Strategy Development

Based on the defined target market and VTS targets, the control strategy should focus on improving fuel economy by at least 15% over the stock figure. Therefore, the selected architecture and components were analyzed based on the potential for fuel economy improvement. The main focus of this research went into the development of the control strategy explained below. This covered the conducted research to evaluate the most suitable solution for the selected architectures and components, the implementation into the Matlab Simulink as well as the debugging and validation based on the given drive cycles and the set VTS targets. Again, training was provided to the team allowing them to understand made decisions.

6.1 Architecture and Component Characteristics

Due to the low energy capacity of the GM Malibu battery pack, purely electric driving and advanced torque split operation was deemed to be inefficient. Pure electric driving in city driving situations will drain the battery pack from its upper SOC limit to its lower SOC limit within five minutes of driving. Nevertheless, the high power capabilities of the battery pack and the EM allow the system to use electrification for hard acceleration and regenerative braking over a short timespan. Higher regenerative braking capabilities are desirable with the chosen architecture since regenerative braking is the only possibility to charge the battery pack. Further, the increased LV loads caused by the added controllers and CAVS had to be considered when designing the LV system. Different LV system designs were investigated resulting in the most fuel-efficient option, which uses a separate LV system providing all necessary power through the 12V BAS motor. The HV system will have no connection with the LV system. This was driven by the need to utilize regenerated braking energy for operating the rear powertrain instead of supplying the LV loads. Additionally, the BAS motor can assist and load the engine improving fuel economy by shifting the engine operation points towards more efficient values. This can be used to improve the fuel economy of the chosen engine. The 1.5L Engine was chosen for its higher fuel efficiency. While it has less power compared to the other two engines, this is compensated for by the rear powertrain.

Concluding these statements, the control strategy should focus on operating the engine as fuel efficiently as possible utilizing the high power capabilities of the rear powertrain and the torque assist/loading possibilities of the BAS motor. The control strategy must ensure charge sustaining operation over both voltage levels. Separate HV and LV systems were found to be beneficial for fuel economy. Considering the target market, the defined customer has a need for urban and suburban transportation. Therefore, it was important to consider optimal control over both driving situations while designing the energy management strategy.

6.2 Vehicle Functions

Based on the competition requirements and the team goals the following vehicle functionalities are planned to be implemented and therefore were considered while developing the energy management strategy. All features are summarized in Table 17. The focus lies in combining all features in the HEV Drive Mode. EV and ICE Mode will be developed, for on-boarding new team members on a simplified system but will not be used in normal operation

Table 17: Vehicle Functions

Vehicle Function	Description
HEV Drive Mode	Utilizing the EM, BAS and ICE for propulsion with two different voltage levels
Regenerative Braking	Recapturing braking energy with the EM
Torque Assist	Supplying torque from the BAS and EM to support the engine
Torque Loading	Applying a negative torque from the BAS to the engine
Adaptive Control Strategy	Unique engine-oriented control strategy which adapts to different driving scenarios
EV and ICE Mode	Implemented but not used in normal operation

Regenerative braking capabilities with the BAS were investigated but were deemed to include too many uncertainties in ensuring controllability in combination with the ECM and TCM. It will be revisited once the baseline functionality of the powertrain control system is implemented.

6.3 Energy Management Strategy

6.3.1 Structure

The Energy Management Strategy (EMS) was created in a modular structure, which allows different developed parts and algorithms to be tested and verified independently from each other. In this way model functionalities can be easily modified or added, if necessary. From a system safety point of view, potential failures during the development process can also be mitigated by separating the HV and LV algorithms allowing the independent functionality of both systems. While developing the control strategy the level of technical knowledge of the team was considered. It was decided to keep it understandable and avoid requiring strong mathematical understanding out of the scope of younger team members. Therefore, it was decided to develop a simple and unique EMS inspired by a plug-in HEV [68], where novelty should be achieved by utilizing two different voltage levels according to the EM and the BAS motor. Engine supportive actions will be performed by either the BAS motor, the EM, or a combination of both, whereas regenerative braking will be performed solely by the EM. Advanced Start-Stop actions will be conducted by the BAS motor [69]. Adaptability between urban and suburban driving will be achieved by generating different calibrations applicable to the developed control strategy.

6.3.2 Torque Split

As mentioned above the HEV Drive Mode is the main propelling mode. During that mode, all three torque sources are used to provide the required amount of torque. A torque split needs to be defined that fulfills the wheel torque request dictated by the acceleration pedal at any time. It was defined that the torque split shall result in the most fuel-efficient control trajectory. Seeing the architecture and component limitations the torque split will focus on supporting the engine as much as possible, as this has the highest potential of utilizing all components to their fullest. The most fuel efficient operation of the engine occurs when operating along the Optimal Operation Line (OOL). This is defined as operating the engine at a defined amount of torque over all possible rotational speeds to generate the lowest fuel consumption of the engine. Figure 17 shows an example of the OOL, shown in orange, in the context of the engine torque and speed limitation.

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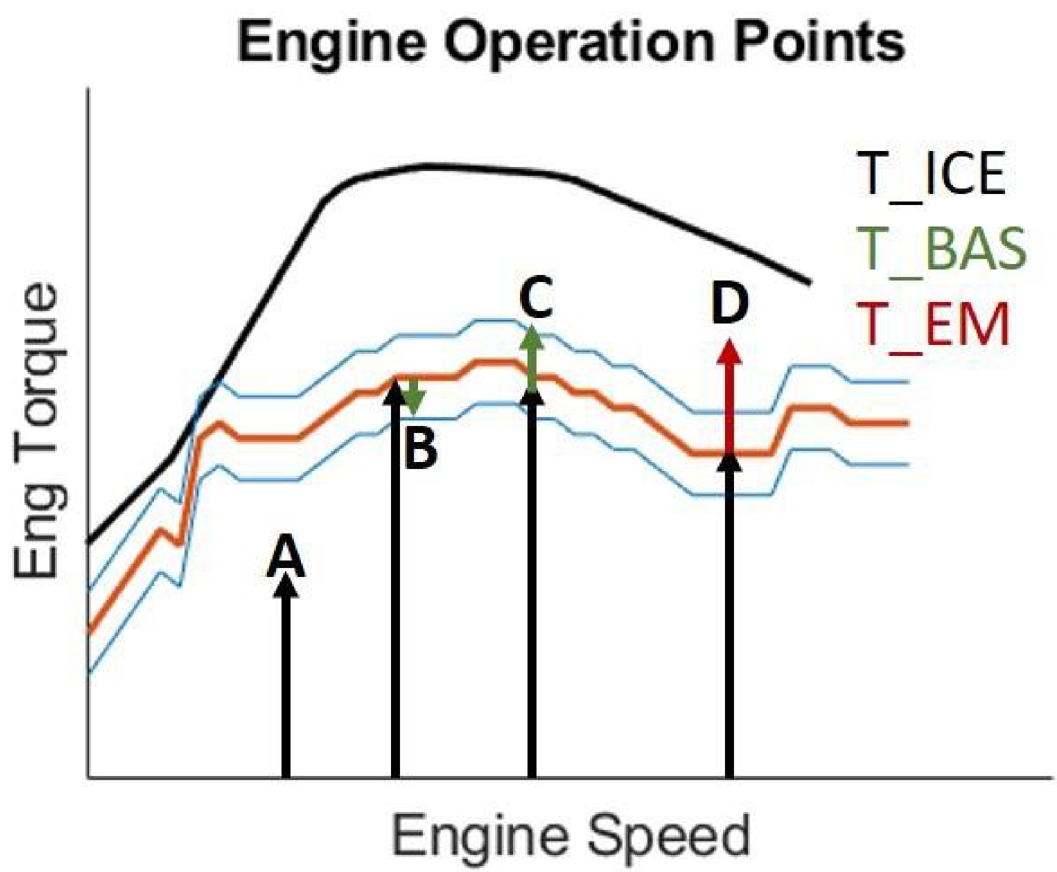

Figure 17: Engine Operation Points for A) ICE Only, B) & C) BAS+ICE and D) EM + ICE

During conventional operation, the engine will operate mainly outside the OOL. In the case of the developed HEV architecture, the BAS motor and the EM can be used to support or assist the engine in a way that allows it to operate on or close to the OOL. In order to determine the amount of torque provided by the EM or the BAS motor, it is necessary to consider their strengths. Based on the power ratings the BAS motor will be used to support or load the engine within its limitations. Point B and C show engine loading and engine support within the BAS limits, shown in blue. Engine loading forces the engine to provide more torque than necessary while the BAS motor is applying a negative torque to fulfill the torque request. This makes sense because the engine will operate at a more efficient operation point and additional used energy will be stored in the LV battery. The stored energy will then be used to support the engine at a later point. If this approach discharges the LV battery to 70% SOC, supportive BAS actions will be reduced to ensure Start/Stop capabilities. Once the torque request exceeds the BAS motor power limits, the rear EM will be used to support the engine. If the power request is exceeding EM motor power limits the engine will differ from the OOL to provide the maximum power of the engine and the EM. During testing over different drive cycles, this situation never appears. However, it appears during acceleration time testing. Finally, if the engine is clearly below the generator power limits of the BAS, the engine will provide all power requests on its own. A dedicated team member is currently investigating the possibility to use the rear EM in combination with the engine in these operation point areas.

6.3.3 Regenerative Braking

Mechanical braking can be done by the disc brakes on each of the wheels and regenerative braking can be done by the EM and the BAS. The only modifications to the disc brakes will be a modified brake distribution. It will be set according to the changed longitudinal weight distribution. Therefore, the disc brake size needs to be reconsidered. Currently, the brake models are considered adequate for all the team's use cases and therefore will not be changed until the team is redesigning the brake system in the future. Additionally, only regenerative braking with the rear EM is being considered. Within these component limitations, series and parallel regenerative braking strategies are possible. Series regenerative braking is defined as a braking operation where until a certain driver braking torque demand the EM fulfills all braking demands. Above the set threshold, the disc brakes and the EM will be used simultaneously. Parallel regenerative braking implies that the mechanical brakes always supply a certain amount of braking force while the EM acts in addition simultaneously [70]. Bounded by the competition rules, series regenerative braking is not allowed. Mainly due to the needed modification of safety-critical components, such as the master cylinder to obtain the necessary pressure within the brake system. Therefore, parallel regenerative braking was chosen and implemented. In this implementation, the deceleration pedal position will be fed through the HSC to be detected by the system. Once detected the EM will be used to request a certain amount of braking torque in parallel to the disk brakes. The amount of torque will be calculated based on the maximum negative torque available at a certain speed. A scaling factor needs to be added to the maximum available torque to avoid unrealistic braking maneuvers, which would influence vehicle dynamics in a dangerous way. This means that based on the deceleration pedal position a factor between 0 and 1 will be applied to allow smoother braking. Equation 22 describes the calculation of the braking torque, where SF denotes the scaling factor and DPP the deceleration pedal position.

Equation 22: Regenerative Torque Calculation

$$T_{regen} = T_{max} * SF * DPP, where\ 0 \leq SF * DPP \leq 1 \qquad \text{(Equation 22)}$$

Figure 18 and Figure 19 show the difference in braking with and without the applied scaling factor over one braking operation. The main difference is the reduced fluctuation of the requested torque, which leads to a reduced fluctuation of the EM speed and the rear powertrain speed respectively. Fluctuation is reduced from 200 rpm per brake action to only 10 rpm, which is considered safe for driving. Nevertheless, a regenerative braking efficiency loss of approximately 20% can be seen. That means that a trade-off between drivability and regenerative braking needs to be found resulting in optimal braking operation.

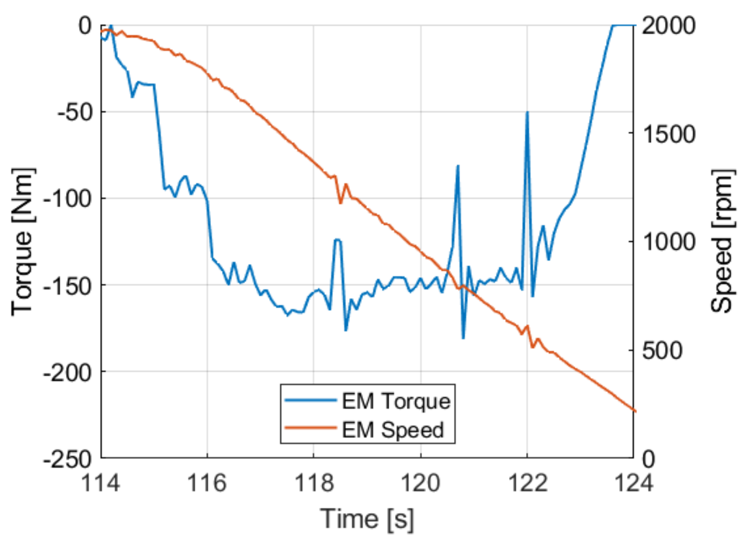

Figure 18: Regenerative Braking with Scaling Factor

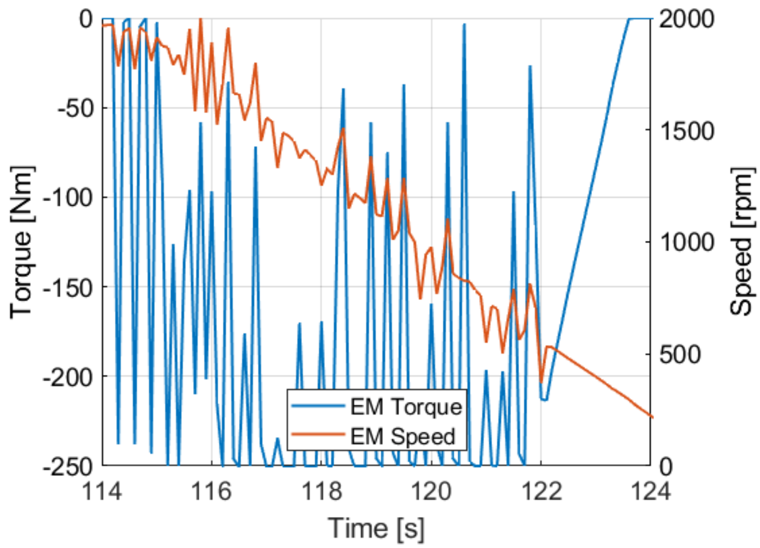

Figure 19: Regenerative Braking without Scaling Factor

6.3.4 Charge Sustaining and Optimization

The mild hybrid application without the possibility of external charging forces the energy management strategy to always operate in a charge sustaining manner. Charge sustaining is defined by ratio of the total net battery energy used over the total fuel energy used represented as percentage. This value has to be within +/- 1%. Unfortunately, solely following the OOL based torque split will not result in a charge sustaining operation. In order to ensure the charge sustaining a charge penalty factor, $CP(SOC)$, was multiplied with a defined torque support range, R , and added to the engine optimal torque command, T_{OOL} , as can be seen in Equation 23 below. In this way, the amount of torque provided by the EM will vary based on the SOC and therefore will ensure charge sustaining while still providing the total requested torque according to Equation 24. Based on the competition rules, only charge sustaining for the HV system is required and therefore will not be considered during operation within the BAS power limits.

Equation 23: Engine Torque Calculation

$$T_{ICE} = T_{OOL} + CP(SOC) * R \qquad \text{(Equation 23)}$$

Equation 24: Total Torque Request

$$T_{total} = T_{ICE} + T_{EM} \qquad \text{(Equation 24)}$$

The defined charge penalty function will vary between -1 when the HV SOC is approaching the set lower limit, and 1, when the HV SOC is approaching the set upper limit. If the target HV SOC is reached the charge penalty function will be 0. SOC limits are set according to the constant power areas of the battery pack occurring between 30% and 60% SOC. Initial and Target SOC will be set to be 45% according to the middle value of the useable SOC range. In between those fixed values, an exponential function was chosen to approximate the charge penalty function. Equation 25 describes the chosen function, where k describes the curvature of the function, SOC_{target} the target SOC and SOC the current SOC.

Equation 25: Charge Penalty Function

$$CP(SOC) = \frac{2}{e^{k(SOC_{target}-SOC)}} + 0.5 \qquad \text{(Equation 25)}$$

The curvature value, k, and the range value, R, influence the charge and discharge behavior and therefore will be adapted based on the faced driving situation. For example, a higher curvature value will increase the steepness of the charge penalty function. That results in a lower effective SOC range and can be useful in situations where a smaller amount of regenerative braking can be expected like in highway driving. Table 18 and Figure 20 show the different charge penalty functions, curvature and range values for two architectures, where Architecture 1 is the team's architecture, and two different drive cycles. Optimization for the curvature and range values were done on a parallel computing cluster set up by the CAVS team.

Table 18: Curvature and Range values

Drive Cycle	Architecture 1		Architecture 2	
	k [-]	R [Nm]	k [-]	R [Nm]
EMC City	**0.6**	**154**	**1.91**	**124**
EMC Highway	**0.94**	**131**	**0.53**	**110**

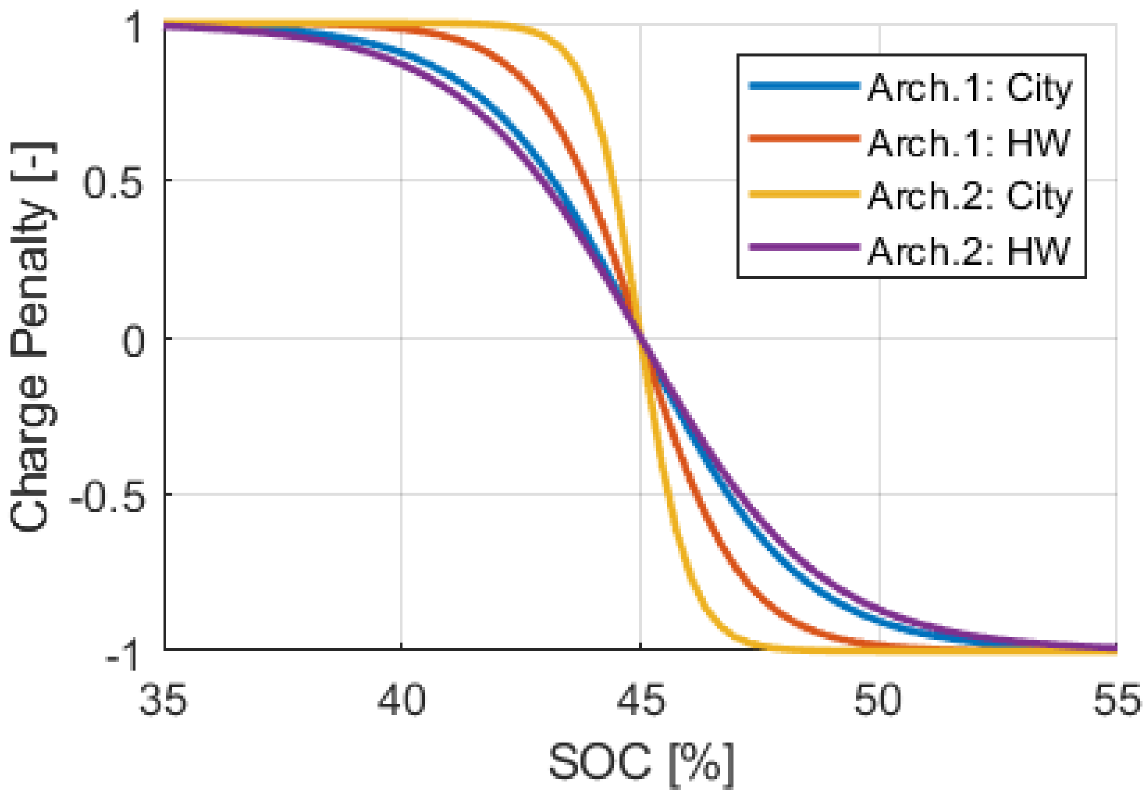

Figure 20: Different Charge Penalty Functions

Figure 21 shows the difference of the engine operation with and without ensuring charge sustaining. It can be seen that fuel economy has to be sacrificed to ensure charge sustaining, which causes engine operation points to differ from the OOL.

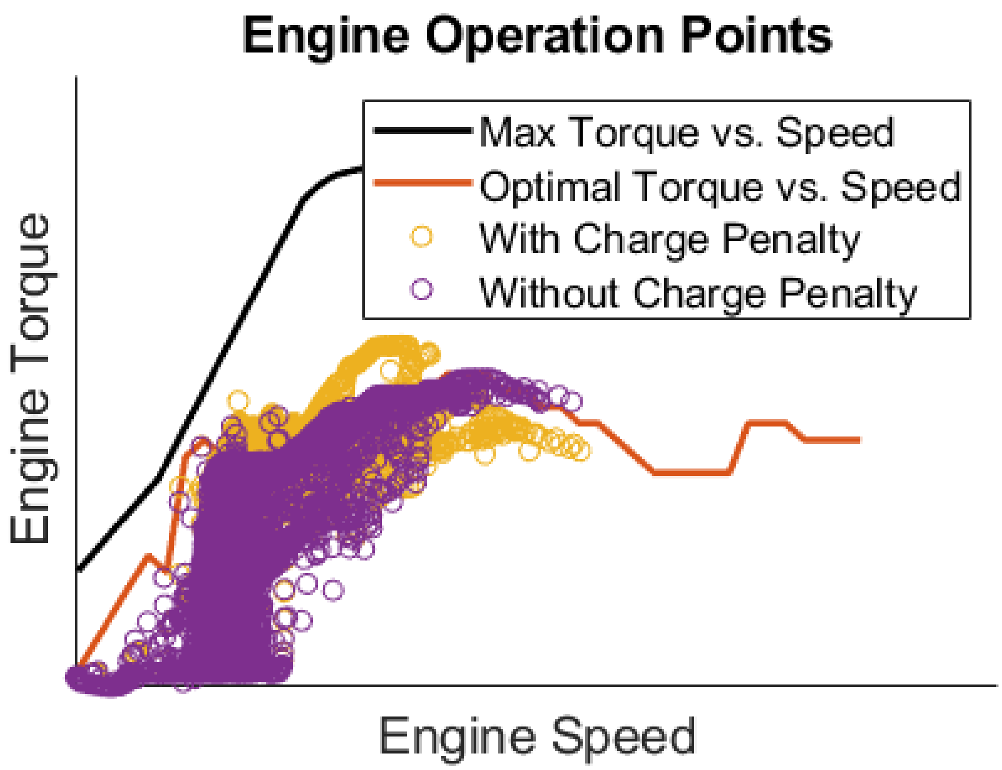

Figure 21: Engine Operation Point [71]

Currently, based on the drive cycle, a different set of parameters will be loaded within the model. Future work will involve investigating the implementation of a Driving Situation Identifier to determine, which set of parameters suits the current driving situation of the vehicle, online and in real time. A simplified approach is implemented where distinction will be made based on the vehicle speed. Additionally, the CAVS will be utilized to help recognize approaching driving situations by for example detecting speed limit signs.

6.3.5 Simulink Implementation

The implementation of the energy management strategy used Stateflow. Each drive mode is defined as a single state calculating and outputting the power request for the BAS, EM, and

Engine. Inputs are the calculated power command, gathered by multiplying the calculated wheel torque command and the actual rotational wheel speed. Depending on the state additional inputs like the acceleration pedal position are used. Overall defined states are Drive_Ready, EV_Mode, HEV_Mode, Start_Stop_Mode, Acceleration Mode, HEV_Mode, and HEV_Mode_Performance. Outputs of the active state will be fed forward to the component control rings, namely the BAS Control Ring, the EM Control Ring and the ICE Control Ring. Inside the component control rings, the power request will be converted into a torque command.

6.3.5.1 Start_Stop_Mode, EV_Mode and ICE_Mode

An external switch will decide, if the vehicle will be used as an HEV, an EV or an engine-only vehicle. Once Drive_Ready mode has been reached, it will check if EV mode is requested. EV Mode is requested by the “Mode” parameter being set to 2. If not the Start-Stop Mode will be entered, causing the engine to start. Figure 22 visualizes that process.

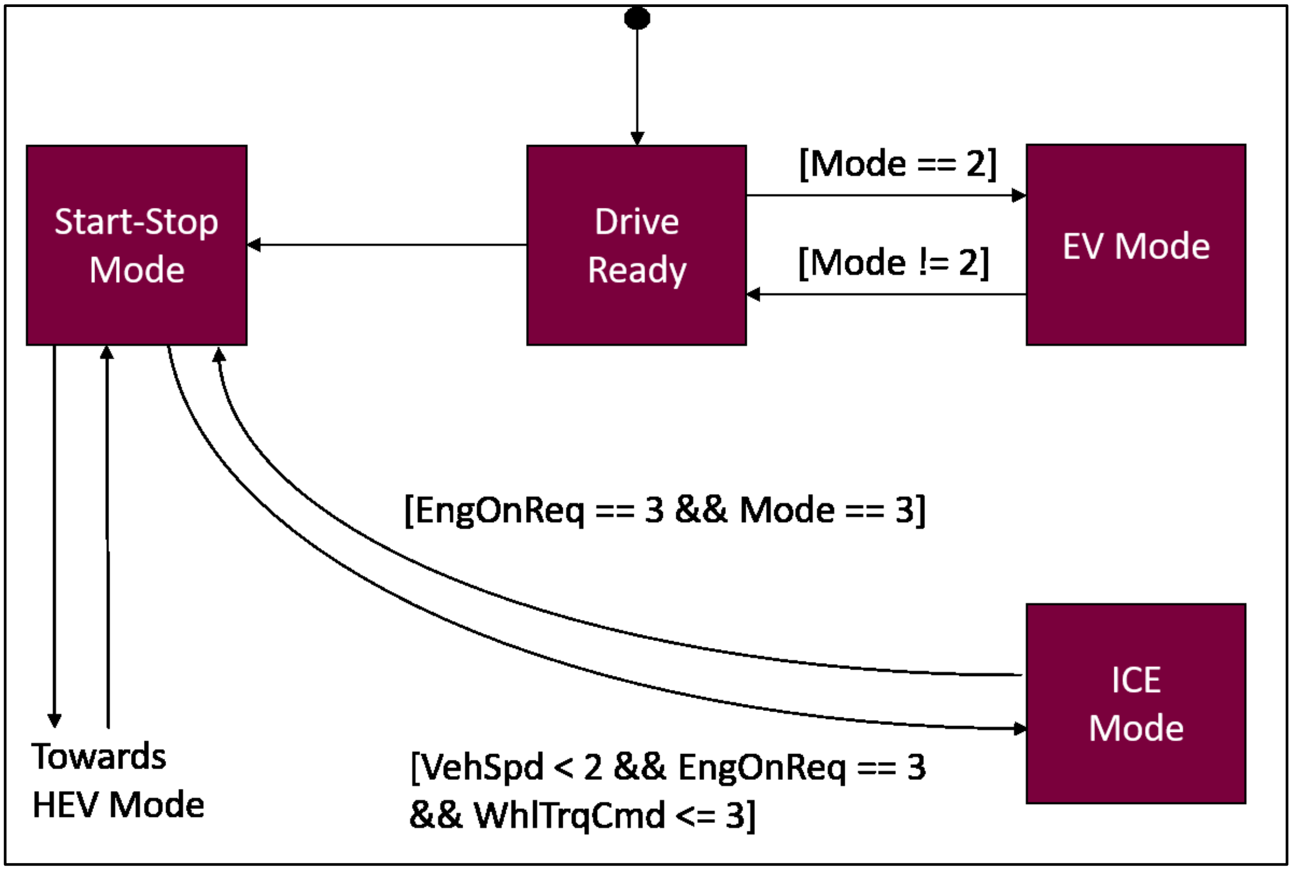

Figure 22: Drive_Ready, EV_Mode and Start_Stop_Mode

If EV_Mode is requested the total power command will be fulfilled by solely the EM within its power limits set by a saturation block. BAS and engine power commands are grounded and therefore not used. It also sends a “Neutral” signal to the TCM to open the internal clutch in the transmission to allow the front axle to be disconnected from the engine. Currently, this mode does not consider any HV SOC restrictions but will be further improved by team members once needed. Figure 23 shows the implementation, using a Simulink Function, within the EV_Mode.

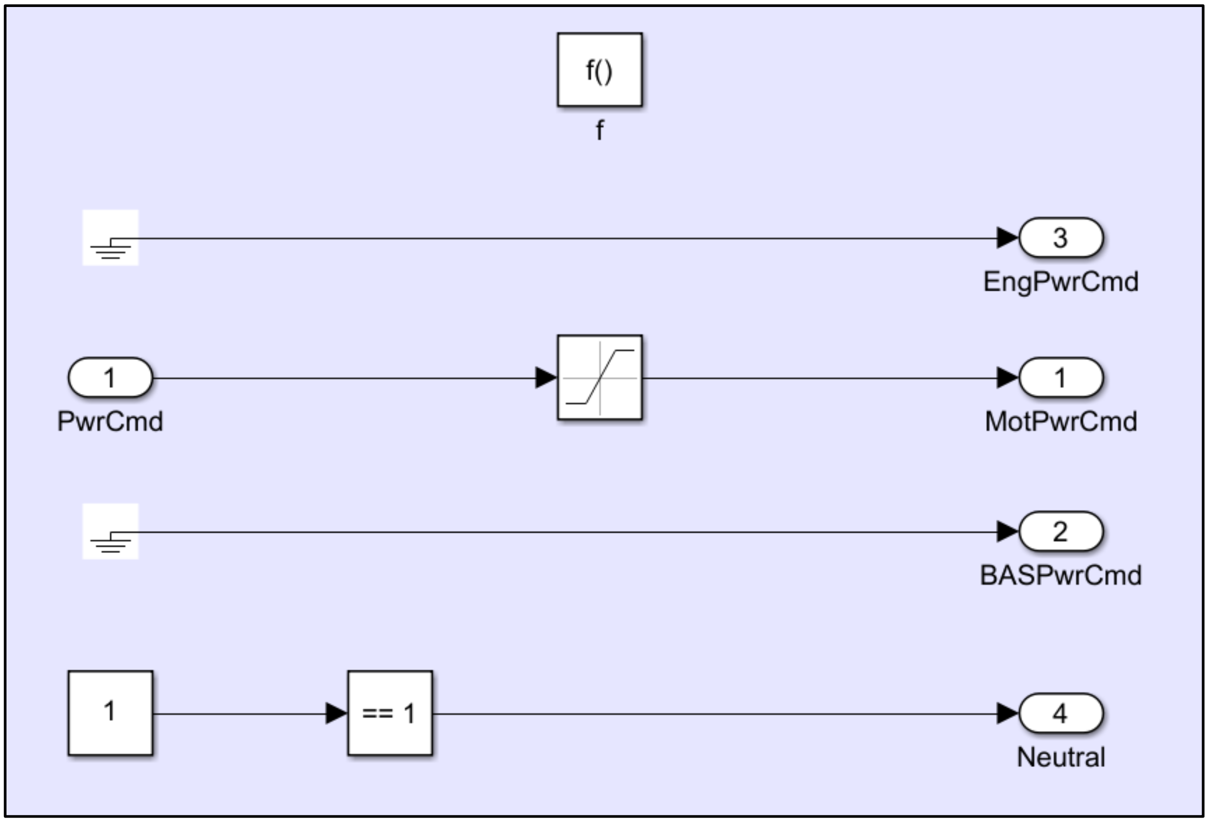

Figure 23: EV_Mode Simulink Function

If EV_Mode is not requested, Start_Stop_Mode will be entered. Inside that mode, all power commands will be sent to the BAS within its power limits. At the same time, the engine receives a power request based on the engine speed to represent the engine starting process. The commanded engine power will be determined by linear interpolation of the idle torque between engine speed equals to 0 and the idle speed. Start_Stop_Mode will be excited by receiving a signal that the engine is started, a speed threshold is reached and either ICE_Mode or HEV_Mode is requested.

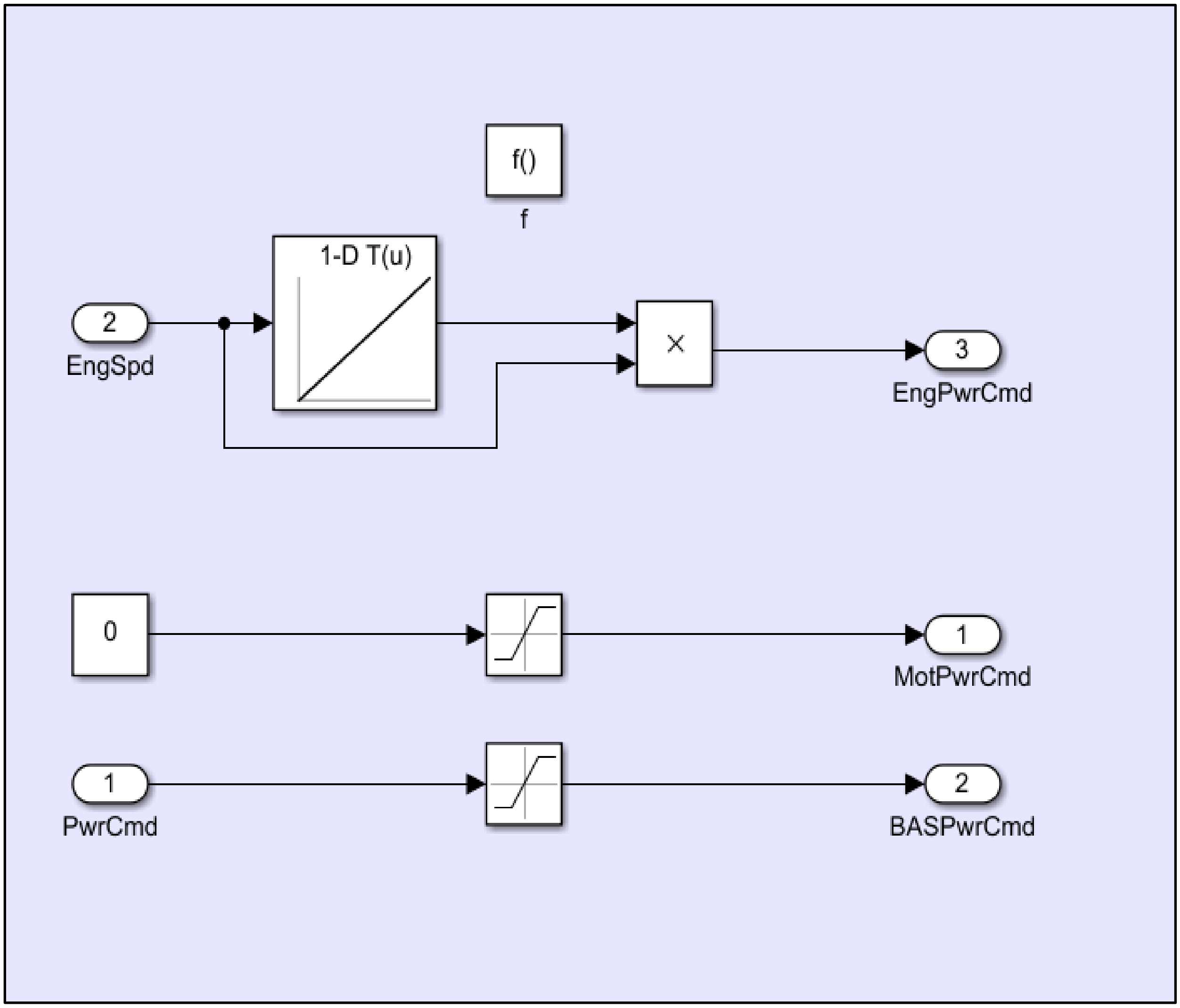

Figure 24: Start_Stop_Mode Simulink Function

If ICE_Mode is requested, the vehicle speed is above 2 mph and the engine is started all power commands will be fulfilled by the engine within its power limits. Figure 25 shows the corresponding Simulink function.

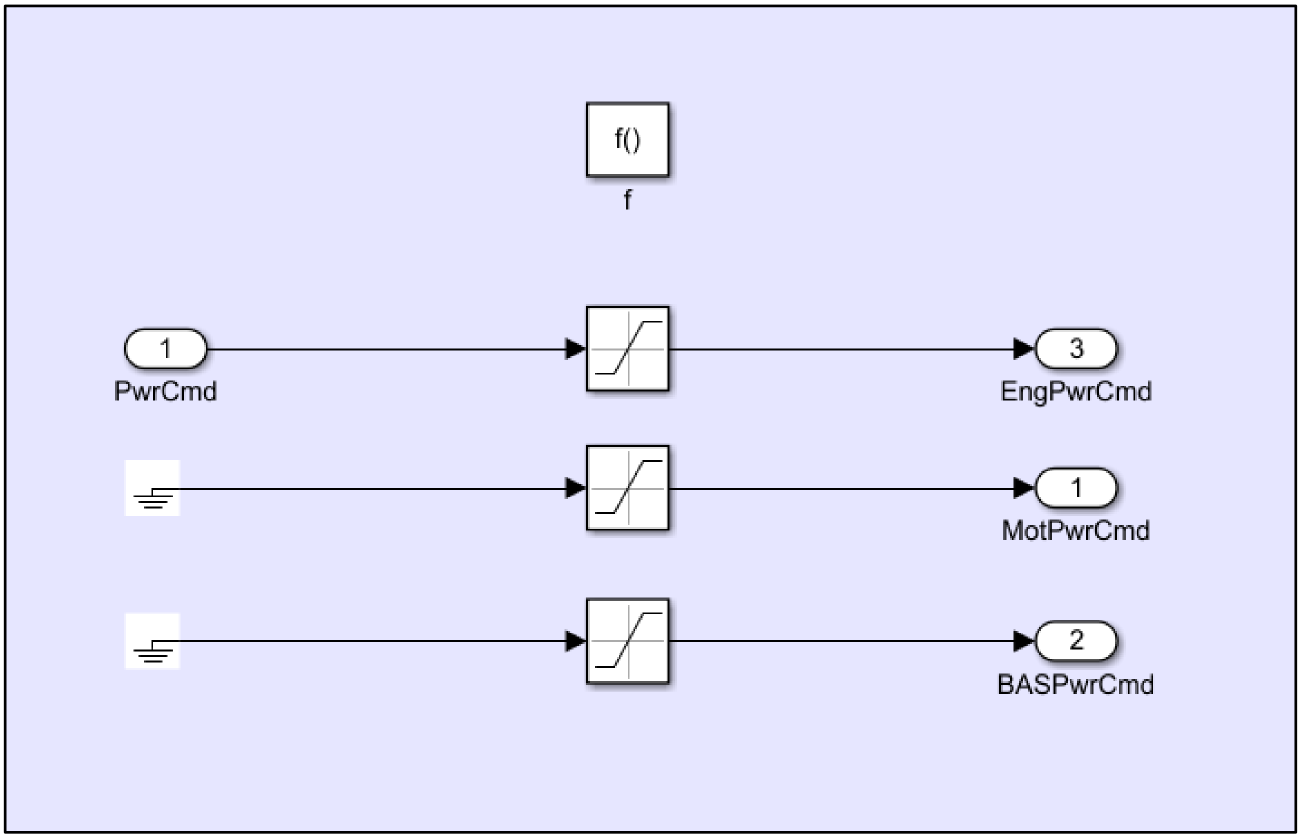

Figure 25: ICE_Mode Simulink Function

6.3.5.2 Acceleration_Mode, HEV_Mode, HEV_Mode_Performance

If HEV_Mode is requested and the vehicle speed exceeds 0.5 mph and the engine is started, HEV operation will be started by going through the Acceleration_Mode, HEV_Mode, and the HEV_Mode_Performance, as seen in Figure 26.

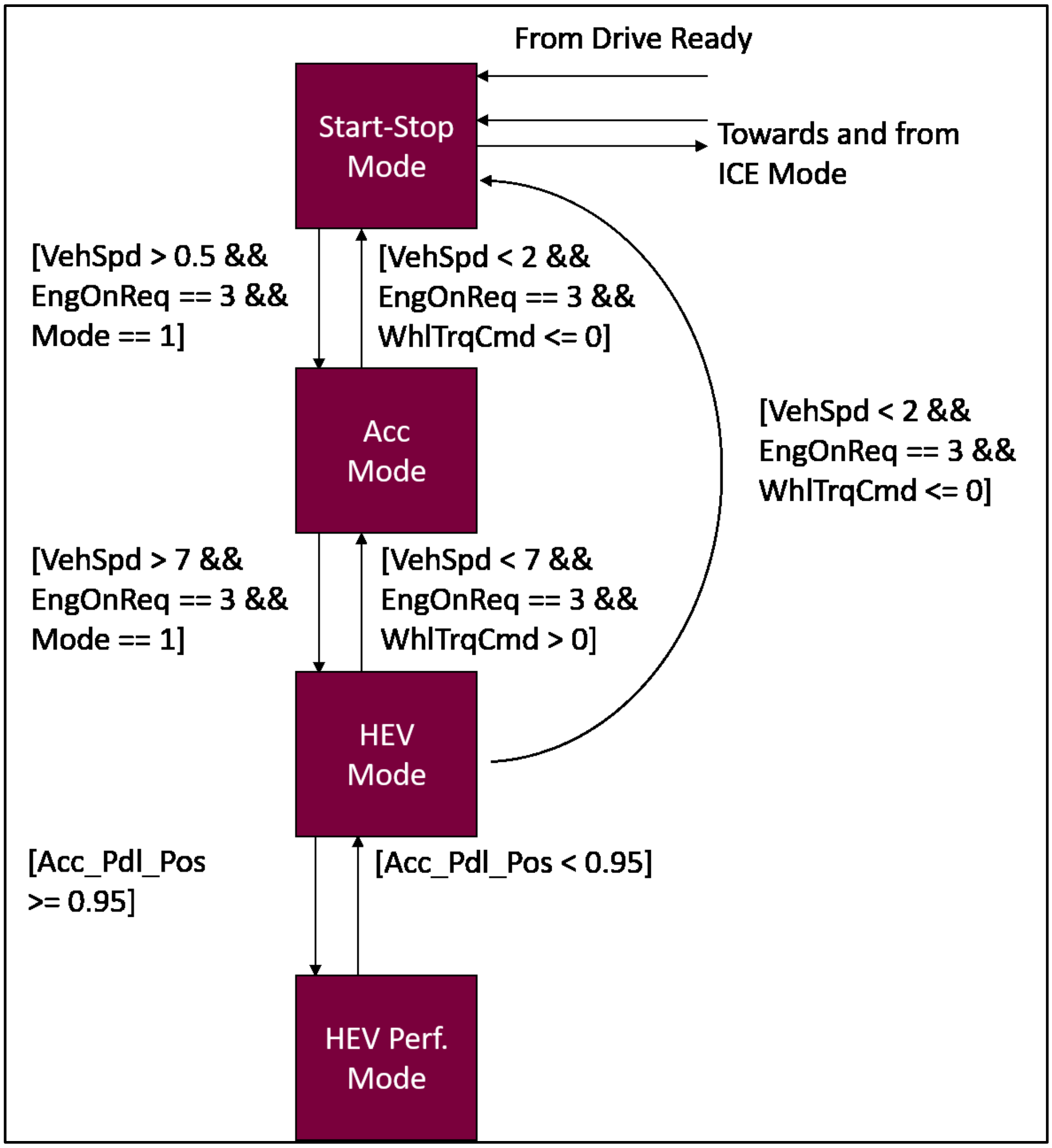

Figure 26: Acceleration_Mode, HEV_Mode, HEV_Mode_Performance

Initially, Acceleration_Mode did not exist, only HEV_Mode and HEV_Mode_Performance were planned. Throughout testing, a lack of acceleration in lower speed areas was detected. Mitigation was accomplished by initiating the Acceleration_Mode before entering HEV_Mode. It was developed by a team member and therefore will not be discussed in detail. In general, it ensures that additional power will be provided by the EM in low-speed areas. Once the vehicle speed exceeds 7 mph Acceleration_Mode will be exited and HEV_Mode will be entered.

In HEV_Mode the discussed EMS will be implemented. Firstly, the engine torque according to the OOL will be determined. The OOL is stored in a LUT and will be determined based on the engine speed. Afterward torque modifications due to charge sustaining operations will be calculated and added to the optimal engine torque. A safety check, in the form of a saturation block, is applied to not request power values exceeding the engine power limits. The power will be calculated by the engine torque and speed and sent to the engine control ring. Also, the engine power will be subtracted from the overall power command, where the leftover is sent to be determined if the BAS motor or the EM will be used.

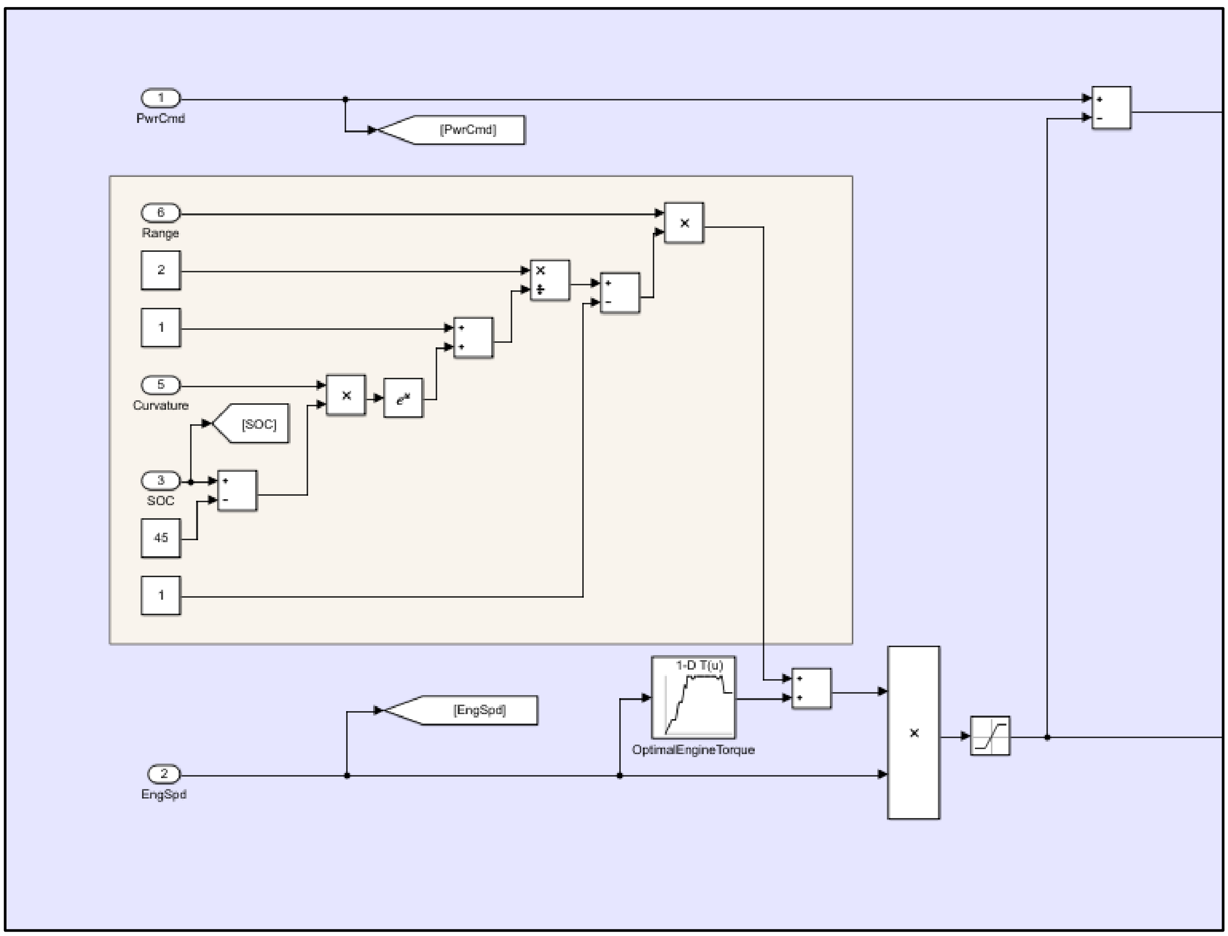

Figure 27: Engine Torque Calculation

Based on the amount of power left after subtracting the engine power, the EMS decides if the EM or the BAS will be used. If the power is exceeding the BAS power capabilities, the EM will be used. Again, power limits are checked with implemented Saturation blocks. In the case of the engine being operated below the BAS generator power a minimum check detects if the engine has to be operated below its OOL.

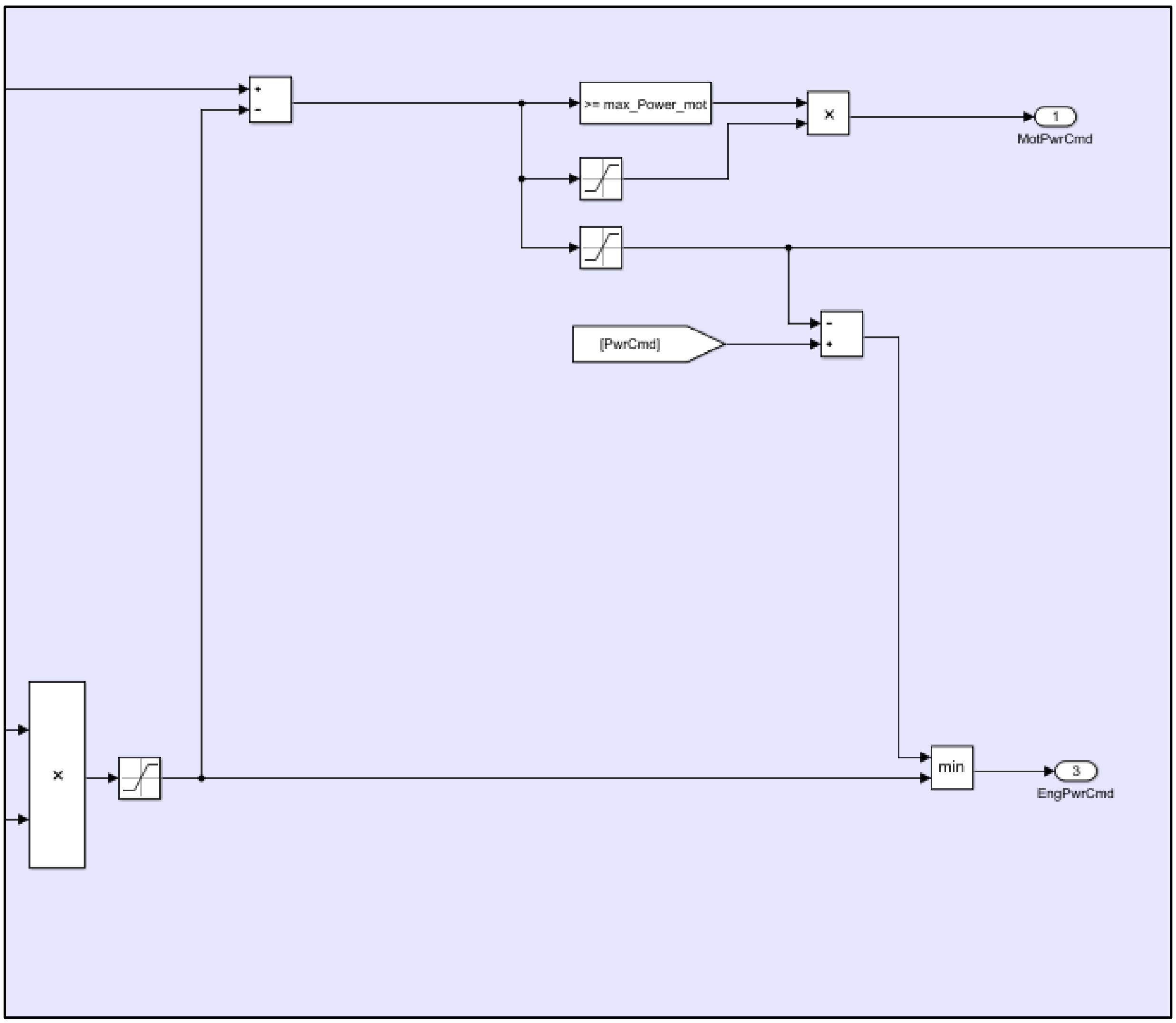

Figure 28: Motor and BAS Power Calculation

Lastly, the BAS power command will be modified to not force the LV SOC below 70% and to stop torque loading operation while the engine is below idle speed.

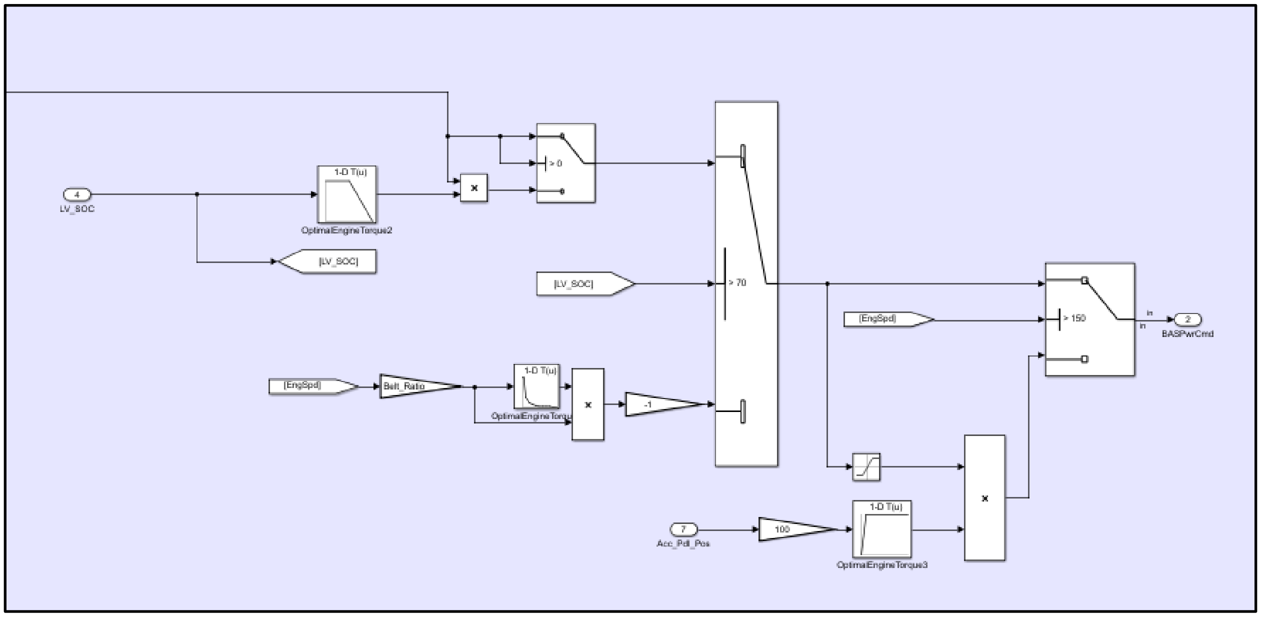

Figure 29: BAS Power Modification

A dedicated team member is in the process of developing the HEV_Mode_Performance state. Currently, it requests maximum power from the engine and EM when the APP exceeds 95%, which is adequate for performance testing. During normal operation over both EMC drive cycles, HEV_Mode_Performance is not necessary.

6.3.5.3 EM Control Ring

The EM Control Ring consists of three states, namely MotOff, MotStart, and MotRunning. States can be identified by the set "MotMode" parameter. Each state is assigned a specific parameter value. MotOff is the initial state and describes the EM while turned off. A torque command of 0 Nm will be sent. Once a power is requested from the EM it switches to MotStart state. An arbitrary rotational speed of 20 rpm is set to start calculating the torque based on the power and the rotational speed. Once an EM torque command is created, MotRunning is the active state. In that state, the torque will be calculated based on the power and the actual speed. Once the vehicle speed is smaller than 0.1 mph and the wheel torque command is smaller than 0, the logic switches back to the MotOff state waiting to be started again.

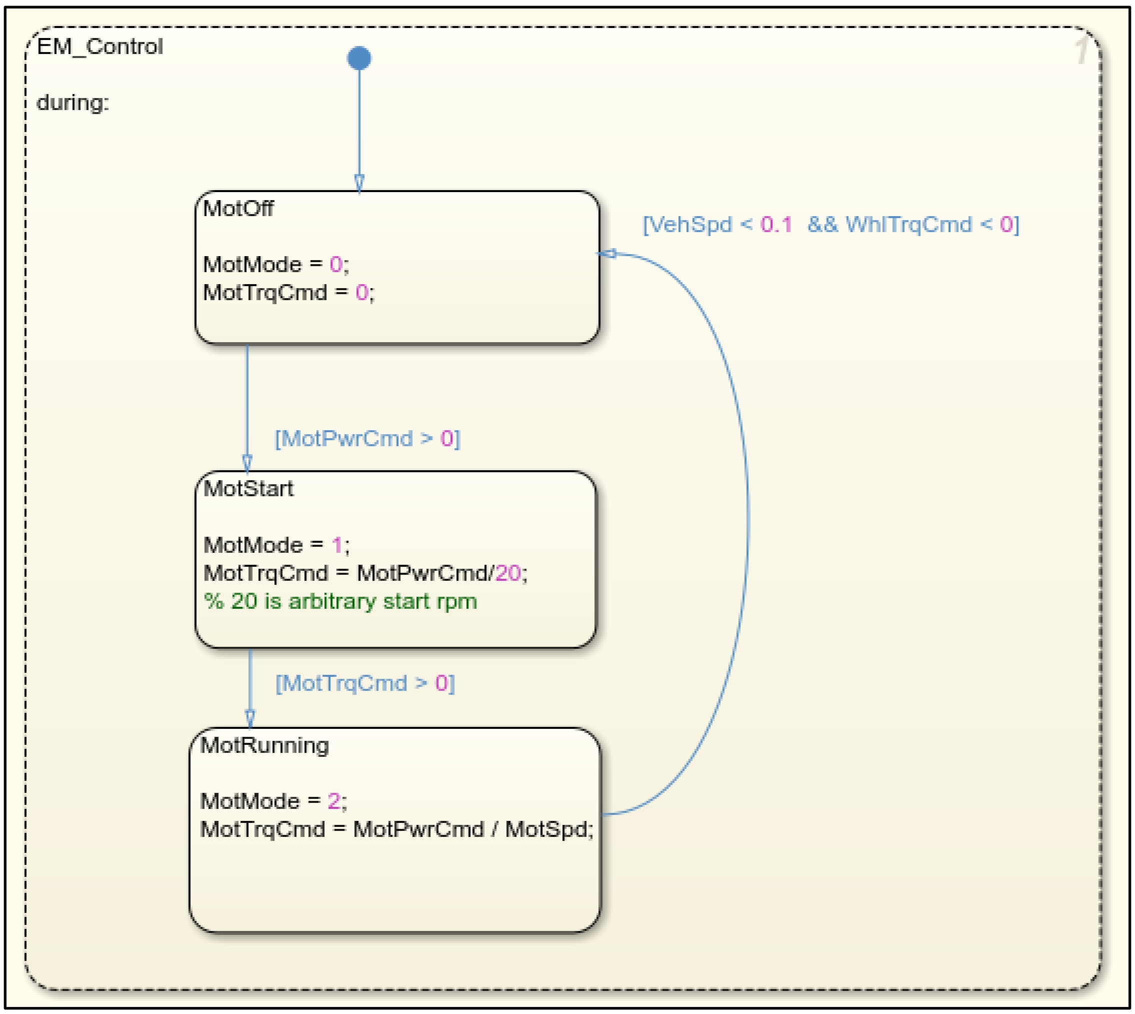

Figure 30: EM Control Ring

6.3.5.4 BAS Control Ring

The BAS Control Ring ensures proper engine starting and torque load/assist while operating. It consists of 4 states, namely “EngOff”, “EngInit”, “EngStarting”, and “EngRunning”. Those states are defined according to the engine state during Start/Stop. ”EngOnReq” is used to track which state the BAS is operating in. “EngOff” state describes the engine when turned off. Once a wheel torque command is sent and the vehicle is not operating in EV, the logic will switch to “EngInit” representing the ignition, requesting a torque from the BAS to match with the idle torque of the engine. This is a necessary state to initialize operation from a standstill point. After 0.1 sec, “EngStarting” will be active requesting maximum torque of the BAS to crank the engine, bringing the engine up to idle speed. Once the engine reaches idle speed the logic will switch to the “EngRunning” state telling the EMS that the engine is successfully started. This will be utilized to switch into HEV_Mode. Once switched to OpMode equals to 0 again, the EMS will switch back to Start_Stop_Mode and command the engine to turn off. Immediate turning off of the engine is avoided by setting a time delay of 2 seconds before the engine can be turned off. Figure 31 visualizes that process.

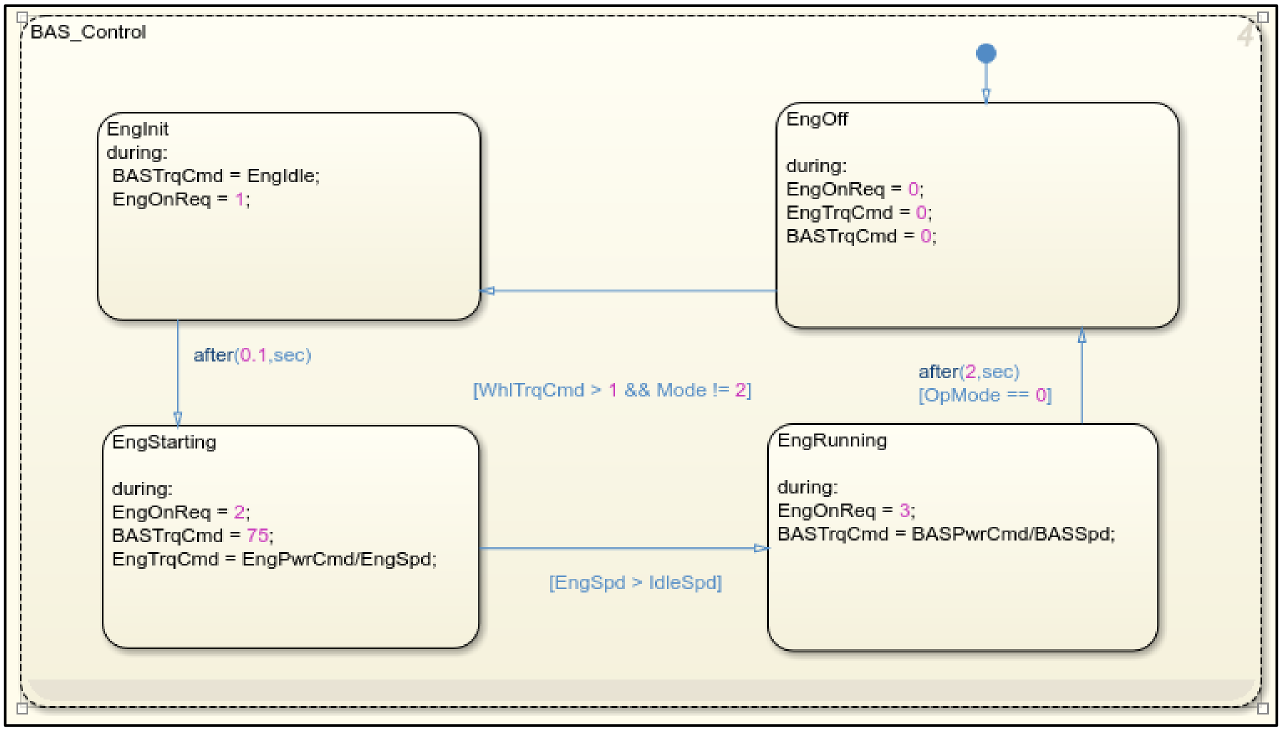

Figure 31: BAS Control Ring

6.3.5.5 ICE Control Ring

The ICE Control Ring determines engine operation once the engine is started. Therefore, it is dependent on a successful engine start process inside the BAS control ring. It consists of four states, where ICE_Stop and ICE_Start are working in parallel to the BAS control. Once "EngOnReq" equals 3 and the engine is stated to be running, the logic will decide whether to use ICE_Idle or ICE_Running. Based on the wheel torque command the engine will idle or provide the determined engine power from the EMS. If the "EngOnReq" equals 0 the engine will go back to ICE_Stop. However, this can only be done if the LV SOC is above 70%. It was assumed that a LV SOC below 70% will not provide enough power to crank the engine again. In that case Start/Stop functionalities are disabled.

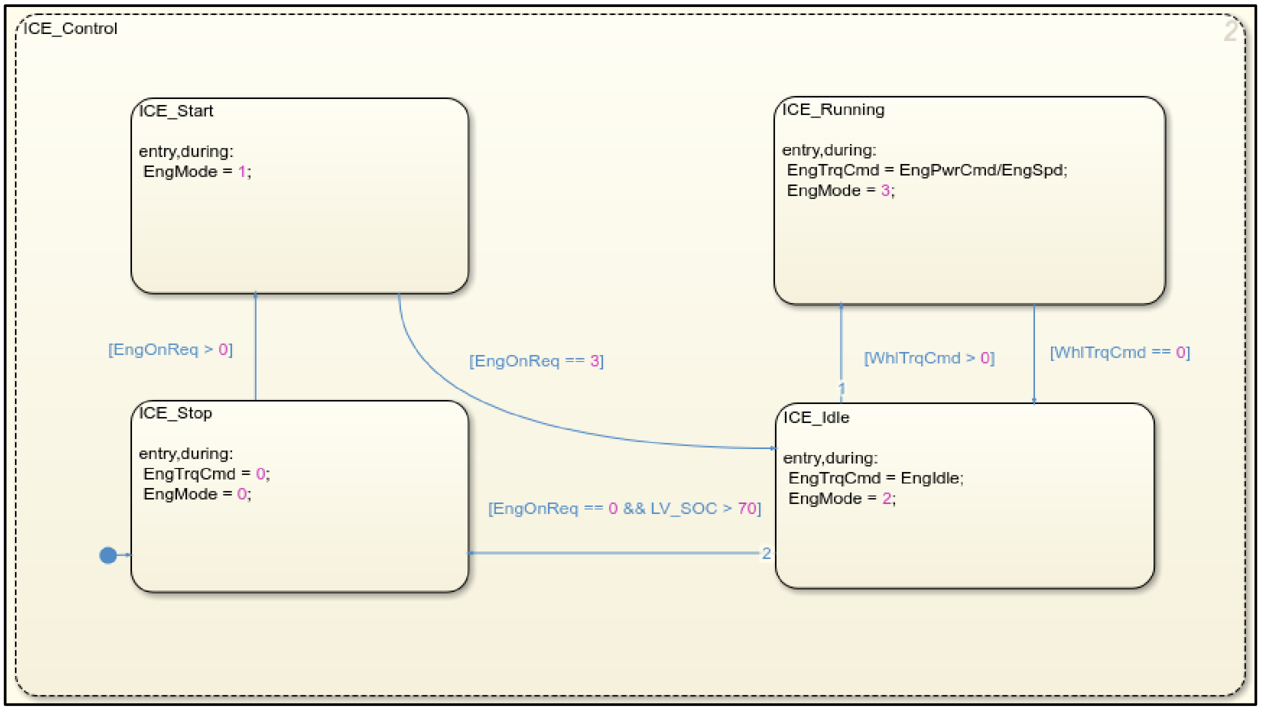

Figure 32: ICE Control Ring

6.4 Distinction from existing research and novelty

Compared to other research, pointed out in paragraph 2.4, the developed control strategy is an improved version of the "Electric Assist Strategy". Following the optimal operation line or the most fuel efficient engine operation point is a common approach to utilize the best of both available energy systems. Changes to that approach were done due the selected architecture and possible further improvements filling up gaps detected in other research.

The selected architecture allows to utilize two electric components for electric support i on two different voltage levels instead only one component. This is a novel setup where the "Electric Assist Strategy" is applied on. Main difference is the BAS motor where the BAS motor and the LV system allow torque loading to improve the engine efficiency while restoring the additional energy into the LV system. This offers torque assist possibilities with the BAS on a larger increasing the usefulness of the BAS motor. Seeing the architecture another distinction is that no functionality is implemented to charge the HV battery pack with the engine. Therefore, regenerative braking is the only possibility to charge the HV battery pack. Operating the vehicle in a charge sustaining manner forces the EM to be used for propelling according the restored energy through regenerative braking. Balancing this is done by the charge penalty function, which is common to be calculated based on the current SOC and a set target SOC. However, instead of using a fuzzy logic approach, like most available research, the charge penalty function is used. This brings the benefits of quicker adaption to new driving situations which will be important for the planned driving situation identifier. Novelty is achieved, not by the used approach, moreover by the application on the unique architecture allowing added and changed functionality to the "Electric Assist Strategy", which shall result in the most fuel efficient operation of the vehicle.

6.5 Summary

The developed control strategy focuses on utilizing all electrification components to support a more fuel efficient operation of the engine while fulfilling the requested torque at any time. Therefore, the OOL is used to determine the amount of torque supported by the BAS and the EM. Additionally, the BAS can apply a negative torque to the engine, allowing the LV battery to be charged, once beneficial. Charge sustaining is realized with a charge penalty function being able to adapt according defined curvature and torque support values. The LV system is ensured charge sustaining by limiting torque supportive actions once a LV SOC limit of 70% is approached.

Implementation of the energy management strategy was done in Simulink utilizing Stateflow. It determines how to determine the power split based on the active operation mode and ensures that a proper torque command is send to each component.

7 Performance and Fuel Economy Evaluation

7.1 Performance Evaluation

Performance evaluation will happen in regard to the team's VTS targets. Therefore, evaluation has to be done over IVM – 60 mph time, 50 – 70 mph time, braking distance 60 – IVM, total vehicle range with 10 gallons of fuel, top speed and gradeability. For each situation a test case was defined to allow automated testing via Matlab Script. Below each test case will be discussed.

7.1.1 IVM – 60 mph time

IVM – 60 mph time will be determined by operating the vehicle in wide-open-throttle operation requesting full power from all used components. Results can be seen in Figure 33. A time of 6.9 sec will be expected fulfilling the VTS target of 7 sec.

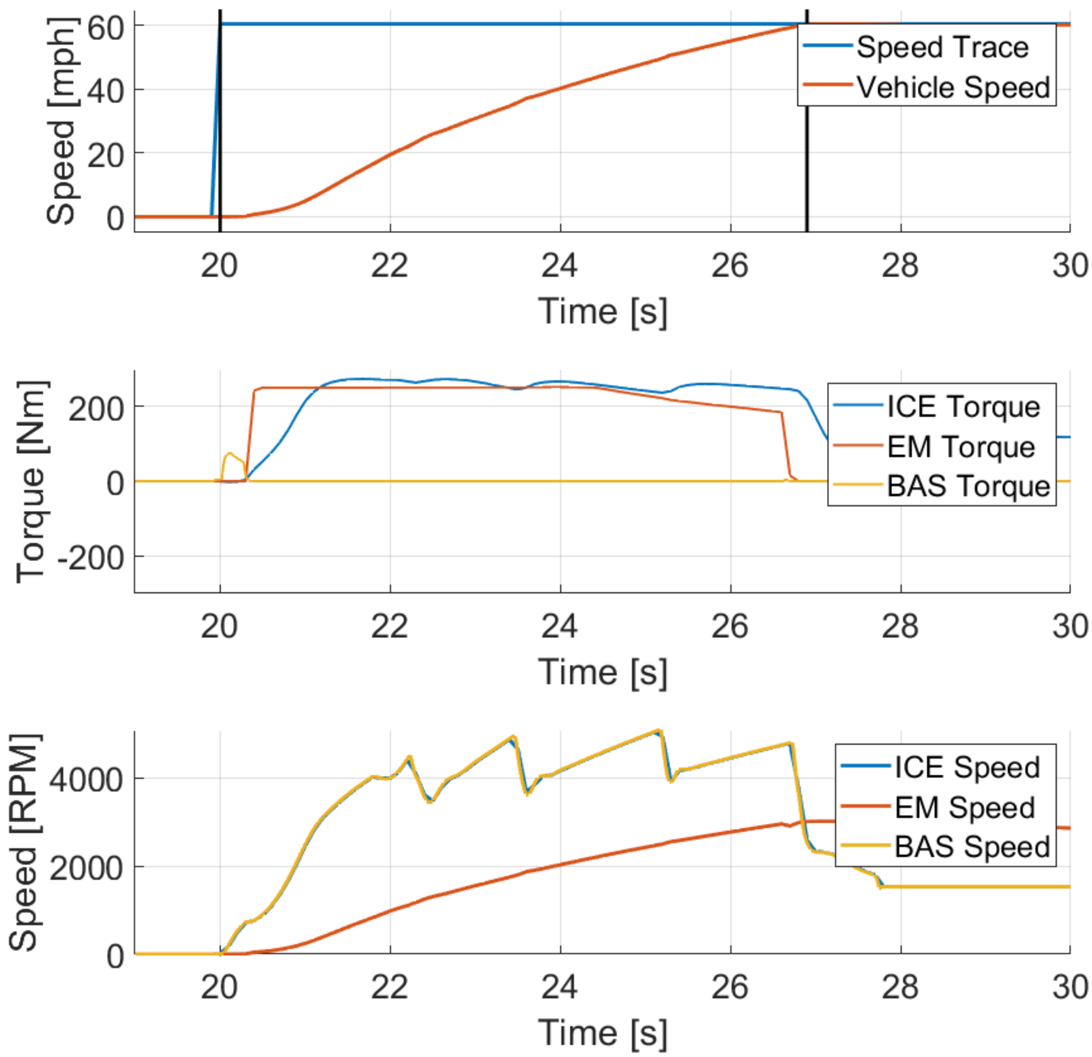

Figure 33: Simulation Results IVM - 60 mph time

7.1.2 50 – 70 mph time

A test case was defined to accelerate the vehicle to 50 mph and further accelerate as fast as possible to 70 mph. The time between requesting acceleration until reaching 70 mph was measured. Figure 34: Simulation Results 50 - 70 mph time shows the powertrain operation.

Based on simulations a 50 – 70 mph time of 5.3 sec can be expected. The team has set this VTS target to be at least 6.5 sec.

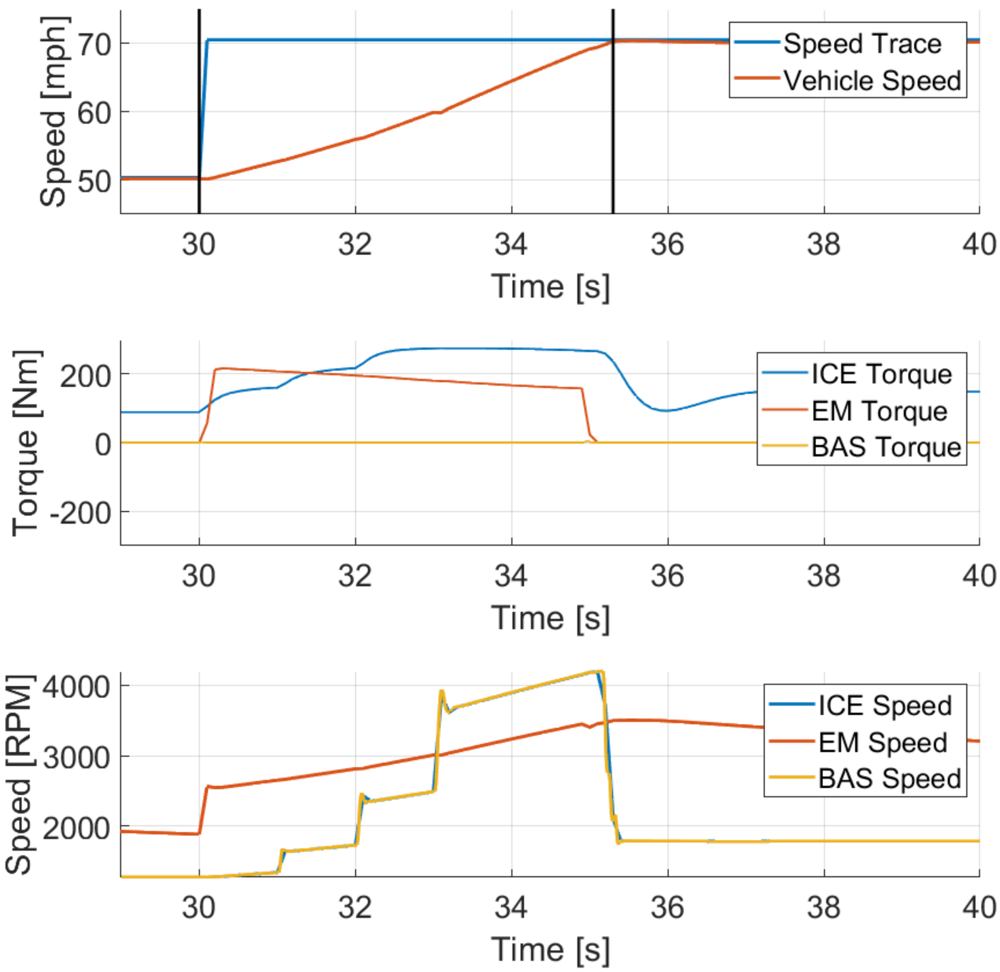

Figure 34: Simulation Results 50 - 70 mph time

7.1.3 Brake Distance

Braking distance was gathered by braking the vehicle from 60 mph to IVM. The traveled distance is measured and estimated to be approximately 158 ft. This means the vehicle will stop within the minimum safety requirement of 168 ft, but not within competition requirement of 138 ft. However, discussion with MathWorks showed that the brake and wheels model are showing model parameter uncertainties and could not be validated. Therefore, once more accurate model parameters are available the braking distance will be revaluated. Figure 35 shows the powertrain operation.

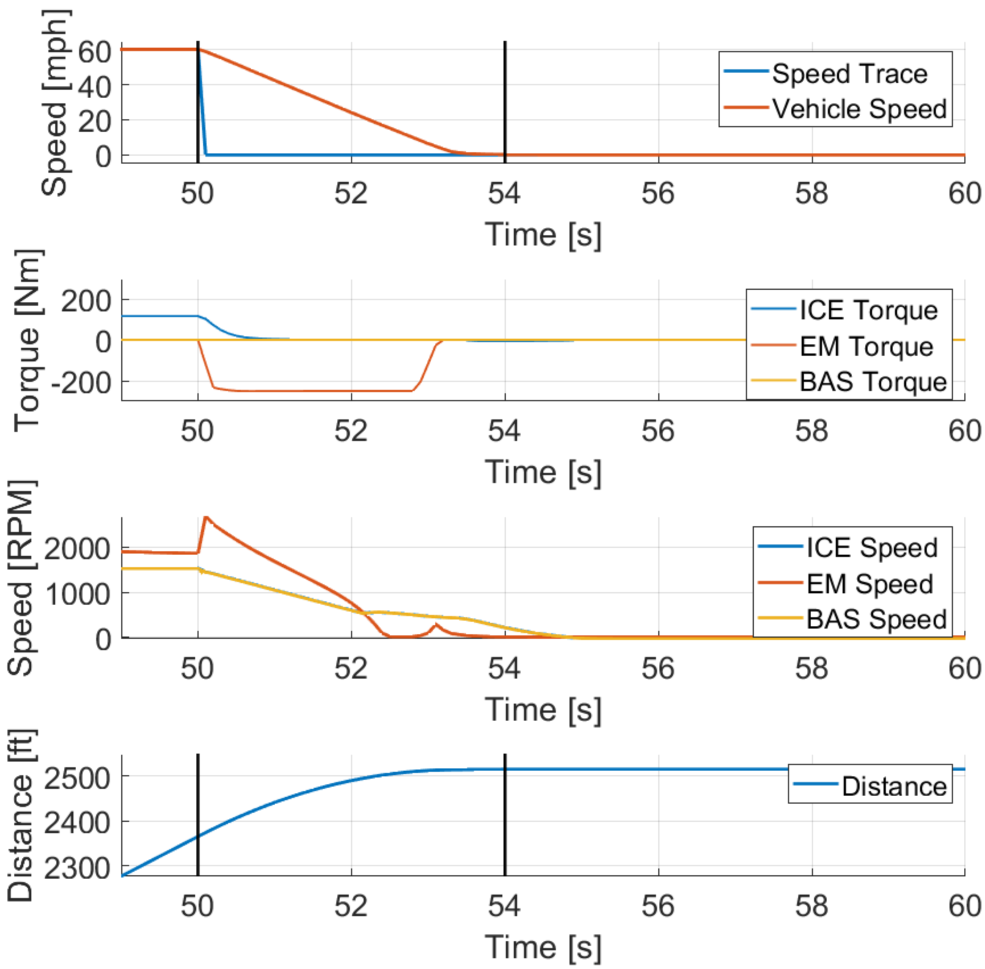

Figure 35: Simulation Results Braking Distance

7.1.4 Vehicle Top Speed

Top Speed testing is done by requesting an unrealistic speed while operating in wide-open-throttle manner. Simulations shows a maximum speed of 122 mph, as can be seen in Figure 36.

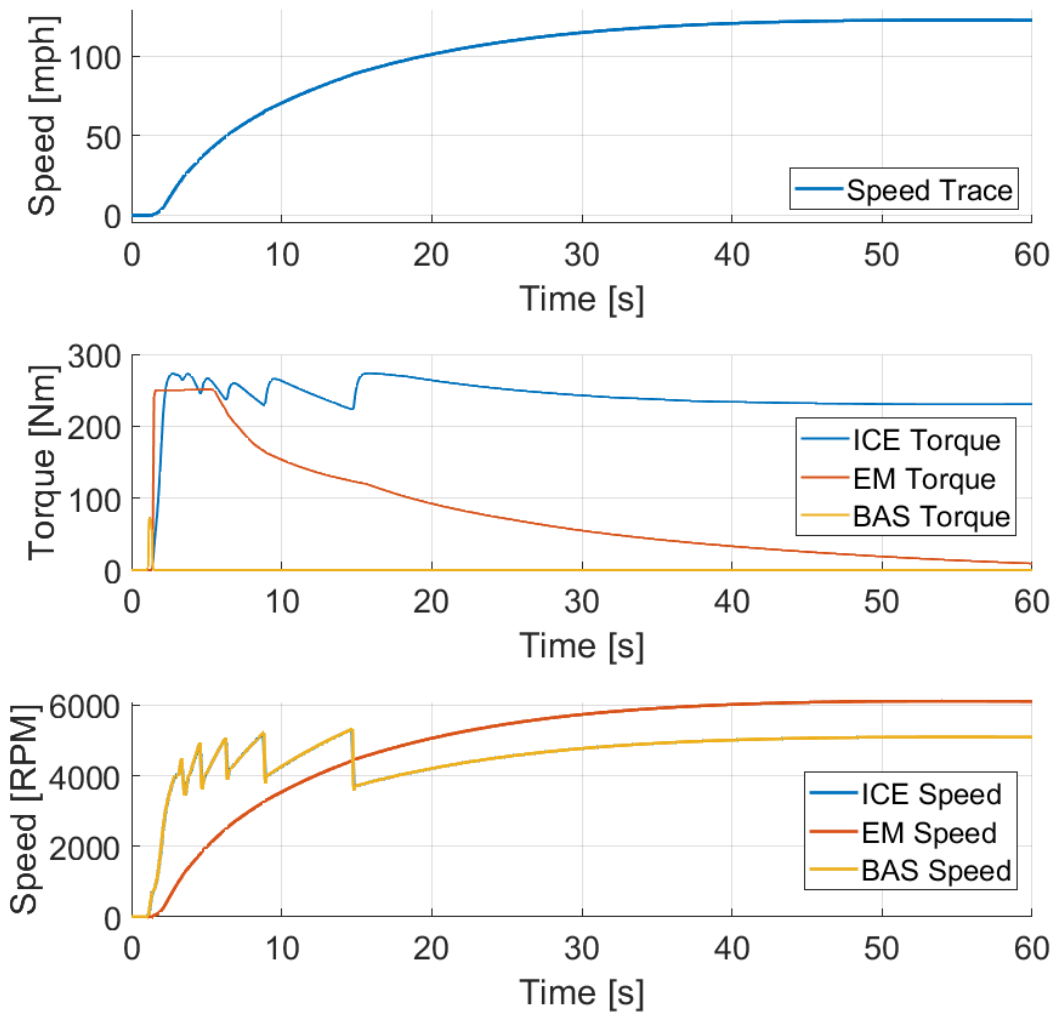

Figure 36: Simulation Results Top Speed

7.1.5 Gradeability

The competition requires a minimum of 3.5% over 20 min at 60 mph. Therefore, gradeability was determined in an iterative manner increasing the slope by 1%, starting from 0%, until the EM has to provide a constant support. If the EM would provide a constant torque, it would deplete the battery fully, which is not desirable over a constant speed driving. Figure 37 shows simulation results for the maximum found gradeability of 8%. It is worth mention that this will never be tested during competition. However, a 3.5% can be expected during actual On-the-Road events.

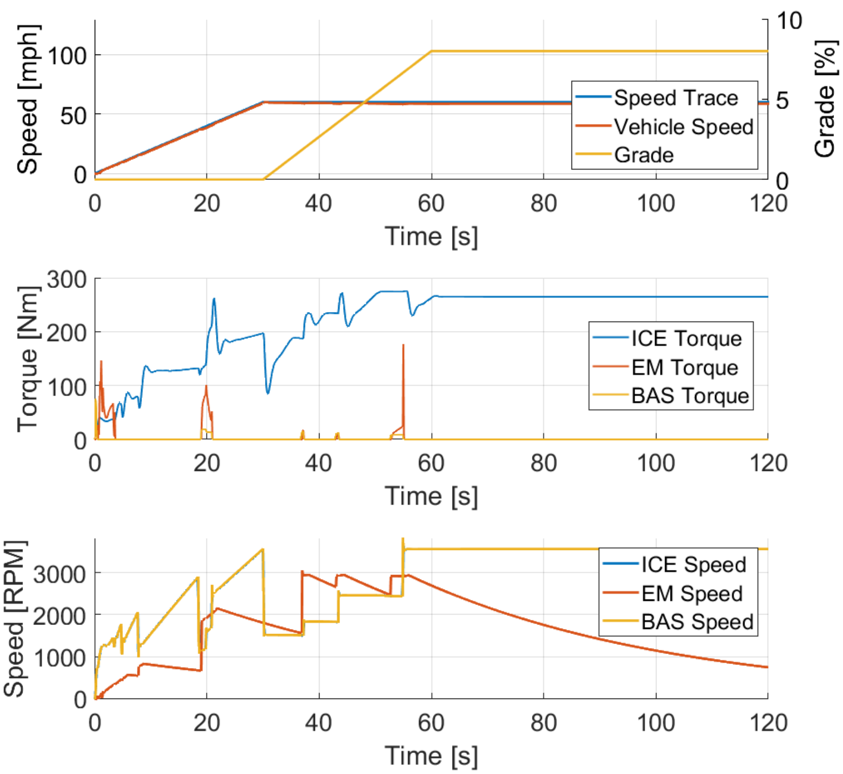

Figure 37: Simulation Results Gradeability

7.1.6 Total Vehicle Range

Total Vehicle Range is determined over both EMC drive cycles until 10 gallons of fuel are used. A range of approximately 291 mile over the EMC City Drive Cycle and 278 miles over the EMC Highway drive cycle can be expected. Both values are exceeding the set VTS of 250 miles.

7.2 Fuel Economy Evaluation

The competition provided two drive cycles representing city and highway driving. Fuel Economy will be evaluated against the performance of the stock Blazer over these two drive cycles. The city cycle consists of parts from the UDDS Phase 1 cycle and the city part of the US06 cycle. Both combined are resulting in the EMC City drive cycle, shown in Figure 38.

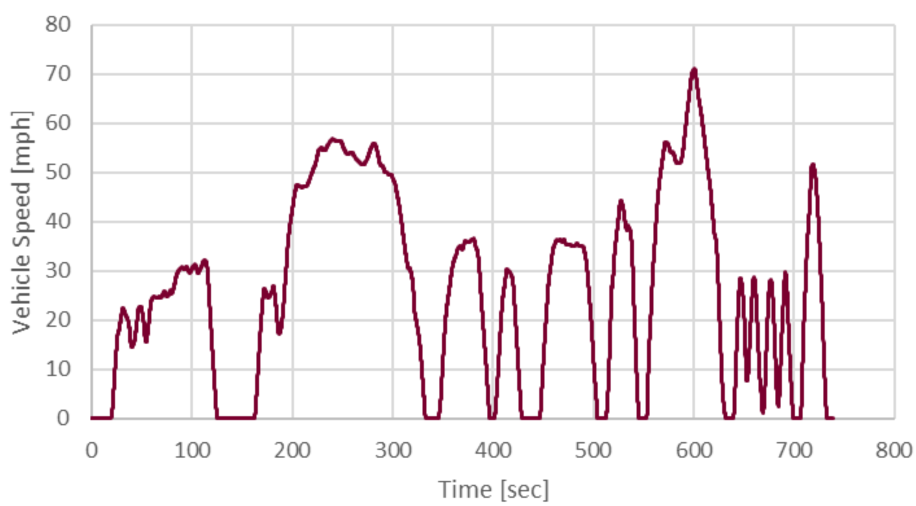

Figure 38: EMC City drive cycle

The EMC Highway Drive Cycle is a combination of the HWFET cycle once and six repetitions of the highway part of the US06. Figure 39 represents the EMC Highway drive cycle.

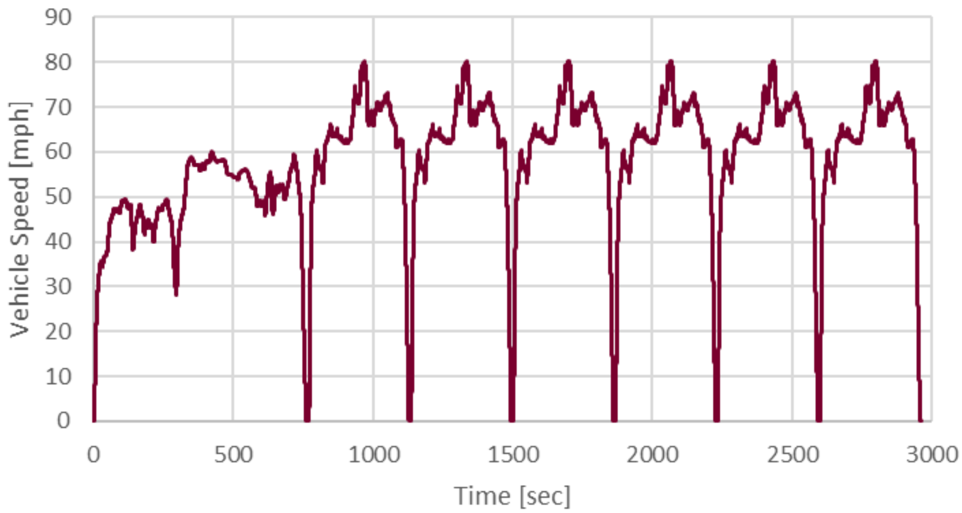

Figure 39: EMC Highway drive cycle

Over both drive cycles charge sustaining must be ensured, and the speed trace has to be followed by the vehicle in an adequate way. Charge sustaining is ensured through the restriction in the EMS, while following the drive trace is ensured through both found driver model set up mentioned earlier.

7.2.1 EMC City Fuel Economy

Fuel Economy improvements of approximately 21% are expected from simulations, resulting in a total Fuel Economy of 31.01 mpg which can be seen in Figure 42. Powertrain operation can be seen in Figure 40. SOC is increasing by 7.7%, resulting in -1.5% of net battery energy used over total fuel energy used. This exceeds the competition requirement of +/- 1%, showing that a too high amount of energy got stored in the HV Battery Pack. It is worth mention that the LV SOC is hitting its lower limit of 70%. For several repetitions of the EMC City Drive Cycle the LV SOC is stagnating around 70%. Further regenerative braking efficiency, the ratio of actual regenerated energy over the total braking energy, is approximately 48% and system efficiency is approximately 43%. Maximum drive traces mises of an absolute error of 2.5 mph can be seen in Figure 41. This results in a Root-Mean-Square Error (RMSE) of 0.46%.

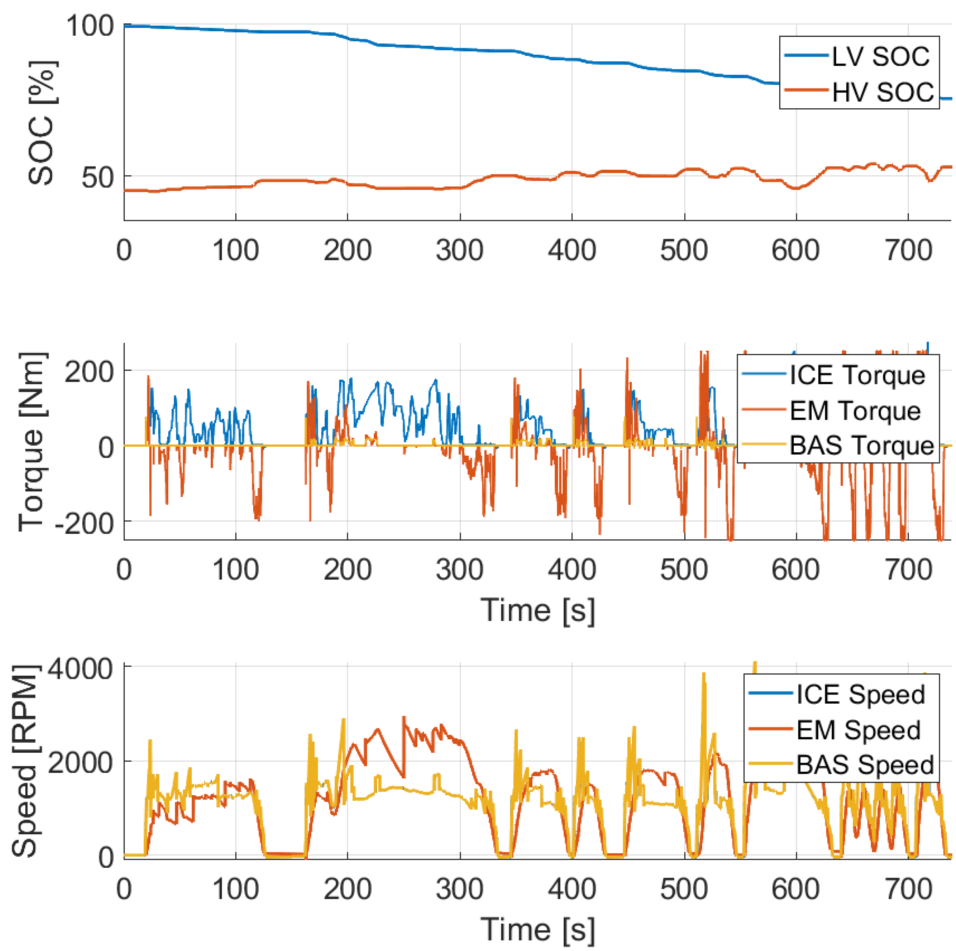

Figure 40: Simulation Results City Drive Cycle

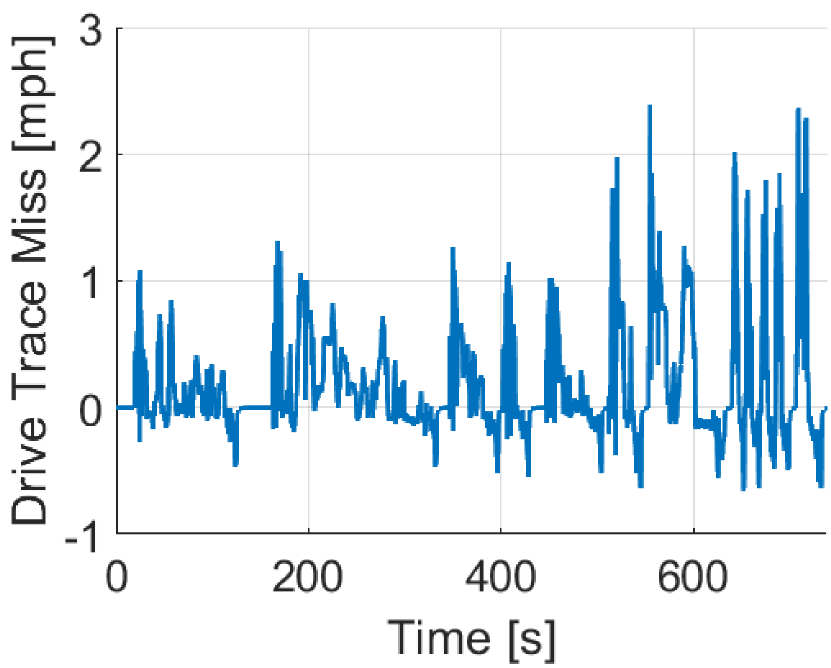

Figure 41: Drive Trace Mises over EMC City

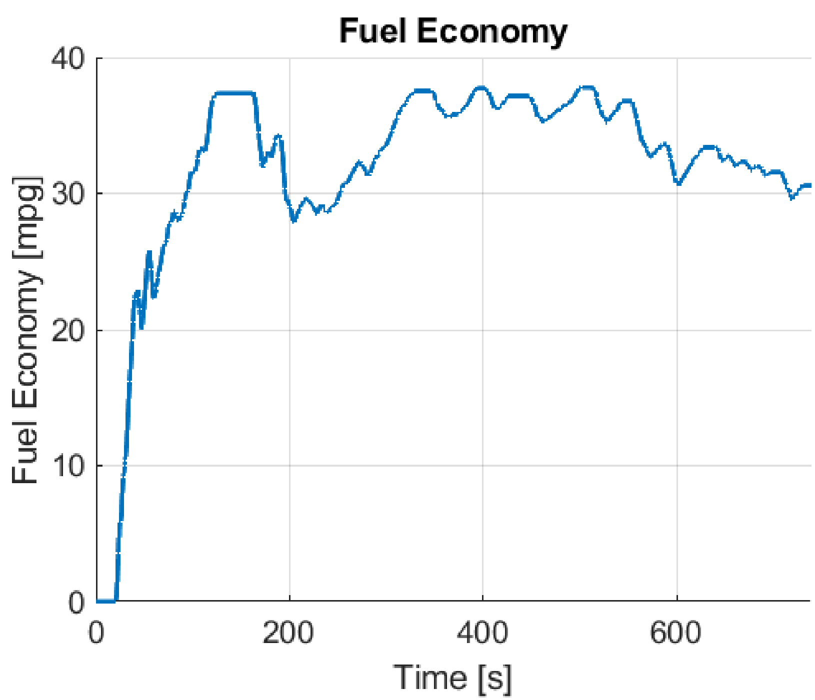

Figure 42: Fuel Economy City

7.2.2 EMC Highway Fuel Economy

Fuel Economy improvements of approximately 6% are expected from simulations, resulting in a total Fuel Economy of 28.05 mpg which can be seen in Figure 45. This lower than the expected 15%. More detailed discussion will be provided below. Powertrain operation can be seen in Figure 43. SOC is increasing by 6.4%, resulting in -0.9% of net battery energy used over total fuel energy used, which is within the competition requirement of +/- 1%. The LV SOC is stagnating around 80% never approaching the lower limit of 70%. This shows a well-balanced use of the BAS in torque load and torque assist. Further regenerative braking efficiency is approximately 24% and system efficiency is approximately 17%. Maximum drive traces mises of an absolute error of 2.3 mph can be seen in Figure 41. This results in a RMSE of 0.44%.

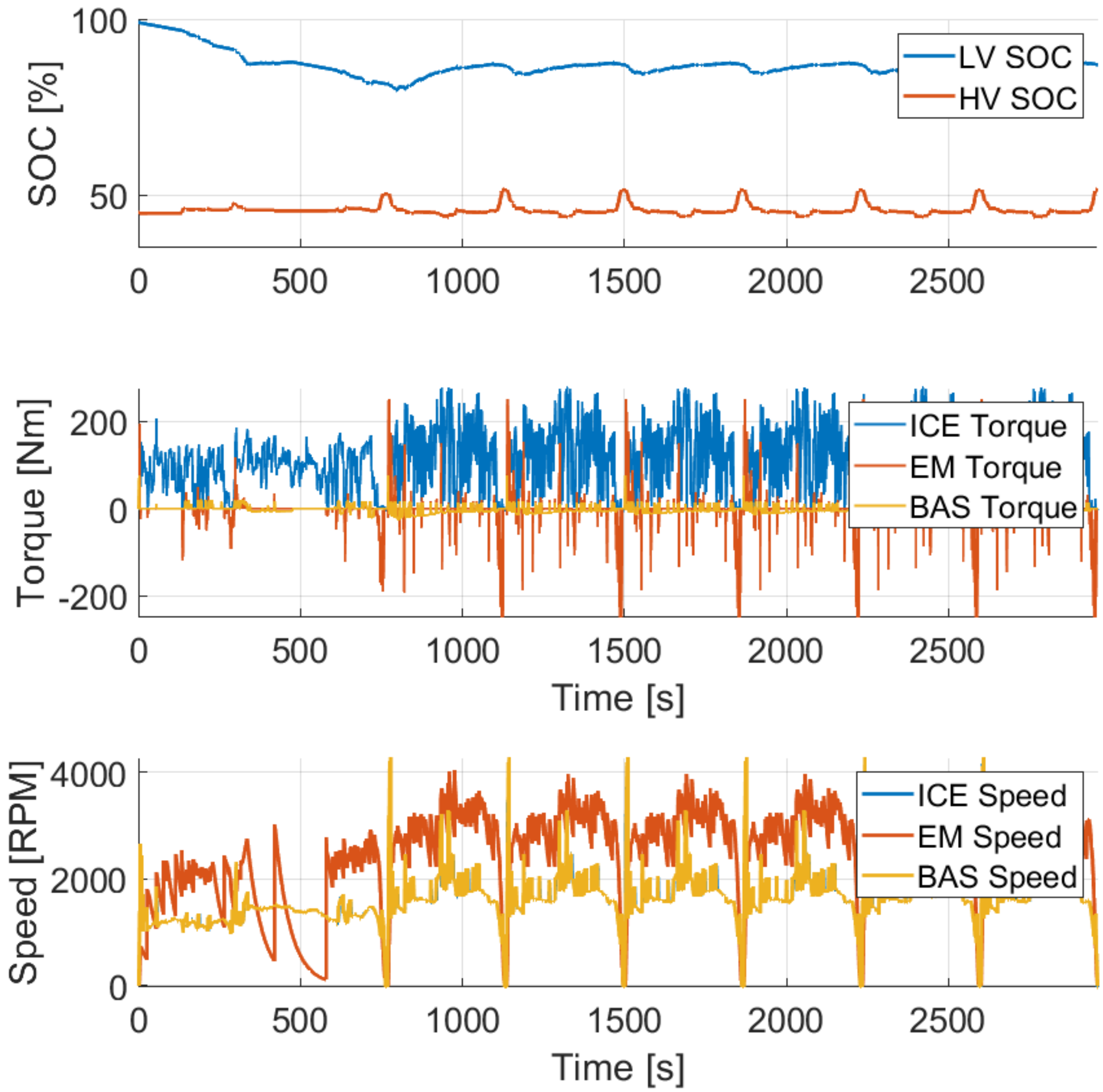

Figure 43: Simulation Results Highway Drive Cycle

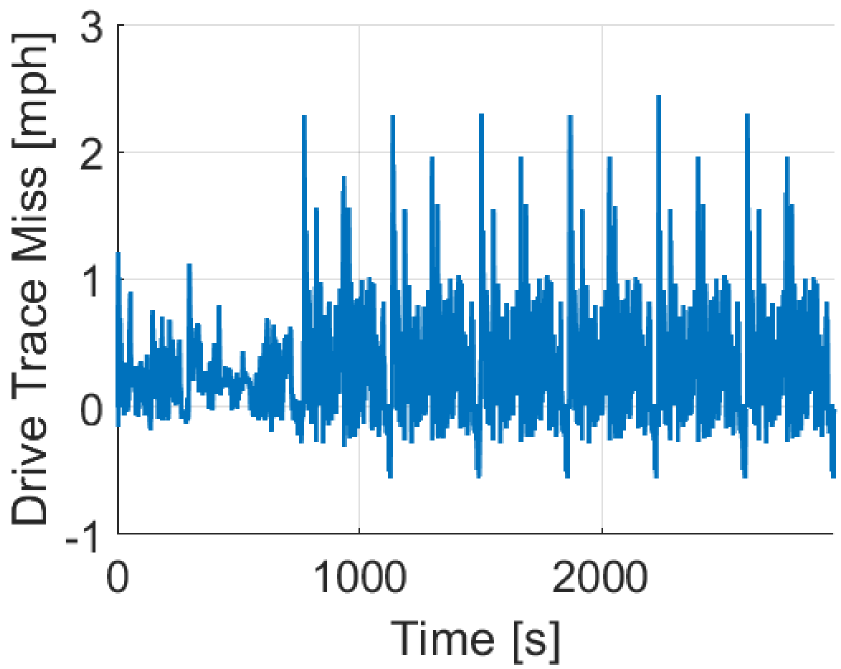

Figure 44: Drive Trace Mises over EMC Highway

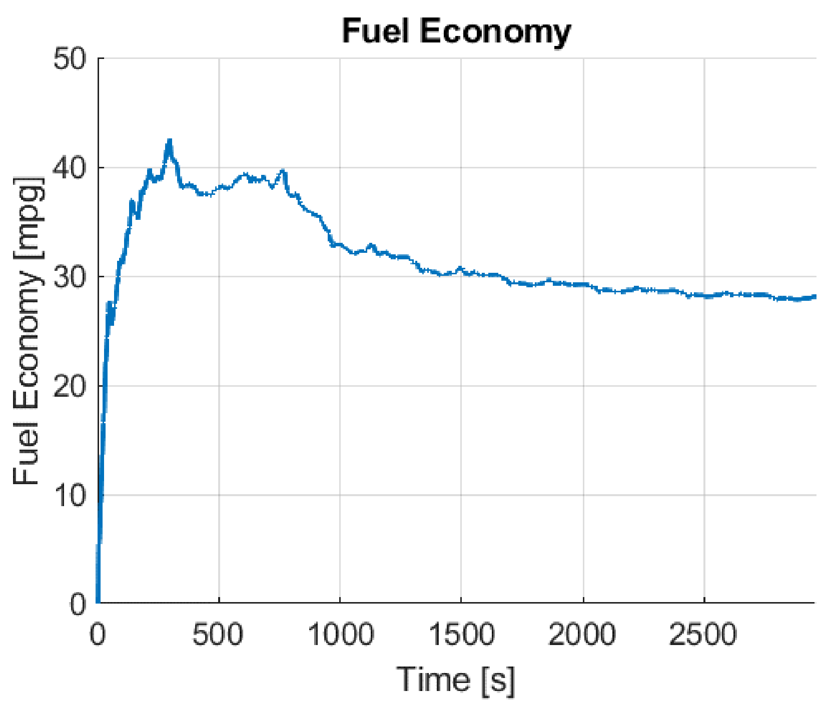

Figure 45: Fuel Economy Highway

7.2.3 EMC Combined Fuel Economy

According to Maven an average carsharing vehicle will face approximately 55% in the city and 45% on the highway. Therefore, the fuel economy will be evaluated over both drive cycles with a weighting 55% on the City drive cycle and 45% on the Highway drive cycle. Equation 26 shows the calculation of the combined fuel economy, where FE denotes the Fuel Economy.

Equation 26: Combined Fuel Economy Calculation

$$FE_{comb} = \frac{1}{\frac{0.55}{FE_{City}} + \frac{0.45}{FE_{HW}}} \quad \text{(Equation 26)}$$

Applying the gathered results from City and Highway testing to Equation 26 results in 11% Fuel Economy Improvement and a total combined Fuel Economy of 29.53 mpg. Figure 46 summaries all fuel economy results.

Drive Cycle	MAC Architecture		Baseline
	FE Improvement	Fuel Economy	Fuel Economy
EMC City	**21%**	**31.01 mpg**	**25.5 mpg**
EMC Highway	**6%**	**28.05 mpg**	**27.9 mpg**
EMC Combined	**11%**	**29.53 mpg**	**26.5 mpg**

Figure 46: Fuel Economy Values

7.3 Discussion

Table 19 summarizes the defined VTS targets and the gathered simulations results. It can be seen that most of the VTS targets are fulfilled. However, braking distance and fuel economy improvements are not sufficient and therefore will be discussed in this chapter.

Table 19: VTS and Simulation Results

Specification	Unit	Competition Target	Team Targets	Simulation Results
Acceleration, IVM–60 mph	[s]	7	7	6.9
Acceleration, 50–70 mph	[s]	6.5	6.5	5.3
Braking distance, 60–0 mph	**[ft]**	**138.4**	**138.4**	**158**
Gradeability (at 60 mph for 20min)	[%]	3.5	3.5	8
Vehicle Top Speed	[mph]	80	80	122
Total Vehicle Range	[mi]	250	250	291/278
Fuel Economy Improvement	**[%]**	**15**	**15**	**11**

7.3.1 Braking Distance

It was considered that the braking distance simulation is shown wrong behavior. This is mainly due the uncertainties in the provided model parameters. MathWorks confirmed that the model parameters will be updated at a later point. Nevertheless, the brake model was shown sufficient functionality but could not be validated. A comparison between the mass and weight distribution of the stock vehicle and the MAC team architecture was made to get preliminary insight on the change of the braking distance. Table 20 shows these parameters. The team is planning to replace the rear disc brakes to face the increased load on that axle. In this way it can be assumed to achieve the same or even better braking distance without relying on simulations.

Table 20: Vehicle Mass and Weight Distribution

Parameter	Stock	MAC Architecture
Vehicle Curb Mass	1985 kg	1922 kg
Weight Distribution	60/40	54/46
Front Axle Weight	1191	1037 kg
Rear Axle Weight	794 kg	885 kg

7.3.2 Fuel Economy Improvement

The simulated Fuel Economy improvement of approximately 11% over both EMC drive cycles are below the set VTS targets of 15%. It is assumed to be caused by conservative assumptions made during the model development. The main identified assumptions influencing the Fuel Economy are the tuning of the regenerative braking strategy, the ratio of the rear powertrain gear reduction and the not implemented Driving Situation Identifier. As mentioned before a balanced tuning for the regenerative braking strategy has to be found, considering drivability and regenerative braking efficiency. Currently the team is focusing on drivability until improved brake and wheel models are available. Based on the simulations with the faulty models, additional fuel economy improvement of 5% can be expected. This is including that drivability is ensured when the rear powertrain can compensate fluctuations of 50 rpm. Additional 2-3% of Fuel Economy improvements can be expected once a fully functional Driving Situation Identifier is implemented [72]. Lastly, a team member initiated to change the gear ratio of the rear gear reduction from 4.4:1 to 5.2:1. It was found that this will increase fuel economy by another 1%.

Table 21: Model Assumptions influencing Fuel Economy

Model assumptions	Expected Fuel Economy Improvement	Validated
Regenerative Braking Tuning	5 %	Simulation
Fully implemented Driving Situation Identifier	2-3 %	Preliminary Simulation and Research

Change of Ratio of rear gear reduction	1%	Simulation

Overall the 15% Fuel Economy improvements should be achievable, seeing the potential improvements laying within the made assumptions. Nevertheless, the team considered to go with the made assumptions to avoid unrealistic simulation results and to have a buffer for potential failure during future years.

7.4 Summary

Based on performance and fuel economy simulations, the selected architecture is resulting in a vehicle working most effectively in a city environment with large amounts of regenerative braking. It was observed that fuel efficiency is directly proportional to the regenerative braking efficiently. This is based on the high power capabilities of the EM and the battery pack. However, minor fuel economy improvements can be seen over highway driving. In numbers, the fuel economy improvements over the EMC City drive cycle is 21%. However, fuel economy improvements over the ECM Highway drive cycle are 6%. Combined fuel economy comes back to approximately 11%. This is below the expected 15% but due the conservative assumptions made 15% fuel economy improvements should be feasible.

Additionally, it can be seen that most of the performance VTS targets are achievabl based on the gathered simulation results. For VTS targets not achieving the set targets, detailed investigations were done to mitigate these errors. Overall the model shows sufficient results and can be used to further years with confidence.

8 Future Work

8.1 Software Development Process

The model needs to be moved from MIL to SIL to HIL testing stage. Therefore, the controller models will be split up according the defined ECUs. This allows to consider the correct I/O dictated by the respective components. This also brings the need of setting up correct communication in a virtual environment between each component. Afterwards software can be developed for each ECU inside the model environment. Once pieces of code are finished the code will be validate either with the dSPACE HIL emulator, on testbenches or inside the vehicle.

Driven by feedback received from industry judges at competition of year 1 a standardized software development process has to be established to face the increasing scope of work and the increasing size of the team in year 2. Currently, in a first iteration of this software development process, motor control code will be written and validated. It is planned to build a dynameter set up, where the HSC will communicate with the Rhinehart MCM to control the YASA P400. A separate model will be built including models of the YASA P400, the MCM and the HSC. The YASA P400 model can be directly used from the original model. The MCM model will be built according the component documentation. It was important to represent the correct I/O and utilizing the correct communications protocol, which is CAN. Different toolboxes will be tested to see how accurately CAN communication can be represented. Lastly, the HSC will be represented utilizing Simulink with ControlDesk. Lastly, the dynameter set up will investigated to acquire the knowledge of controlling the dynameter together with the motor.

This process is highly iterative exploring all possibilities. After each successful step, feedback shall be used to design this process in a more effective way. The goal is to have a established process in the beginning of year 2 allowing each team member to work on developing software in the same manner.

8.2 Driving Situation Identifier

One of the team stretch goals of year 1 was to have a Driving Situation Identifier implemented. This idea is based on previous course work done during my time at McMaster. However, the framework is done implementation still needs to be completed. A Driving Situation Identifier uses, past, present and predicted future driving conditions like acceleration, vehicle speed and distance per stop to characterize the occurring driving situation. A simplified example is to detect if the vehicle drives on the highway or inside the city. On the one hand city driving would be characterised by a high average acceleration, a low average distance per stop, and a low average vehicle speed. On the other hand, highway driving would be characterized by a low average acceleration, a high average distance per stop and a high average vehicle speed. These quantities can be measured and compared to gain insight on the current driving situations. In the case of the developed EMS, this information can be used to select calibrations inside the control strategy which are optimized for either highway or city driving. In more detailed, the curvature value, k, and the torque support range, R, can be adapted online.

Research has shown that simple rule-based approaches can be sufficient. However, a more complex design will be investigated including a machine learning approach [72]. This approach includes a clustering algorithm to determine which driving situations should be considered based on the fed input data. In Figure 47 around 30 drive cycles were considered, colored in black, resulting in the 4 found clusters, colored in red.

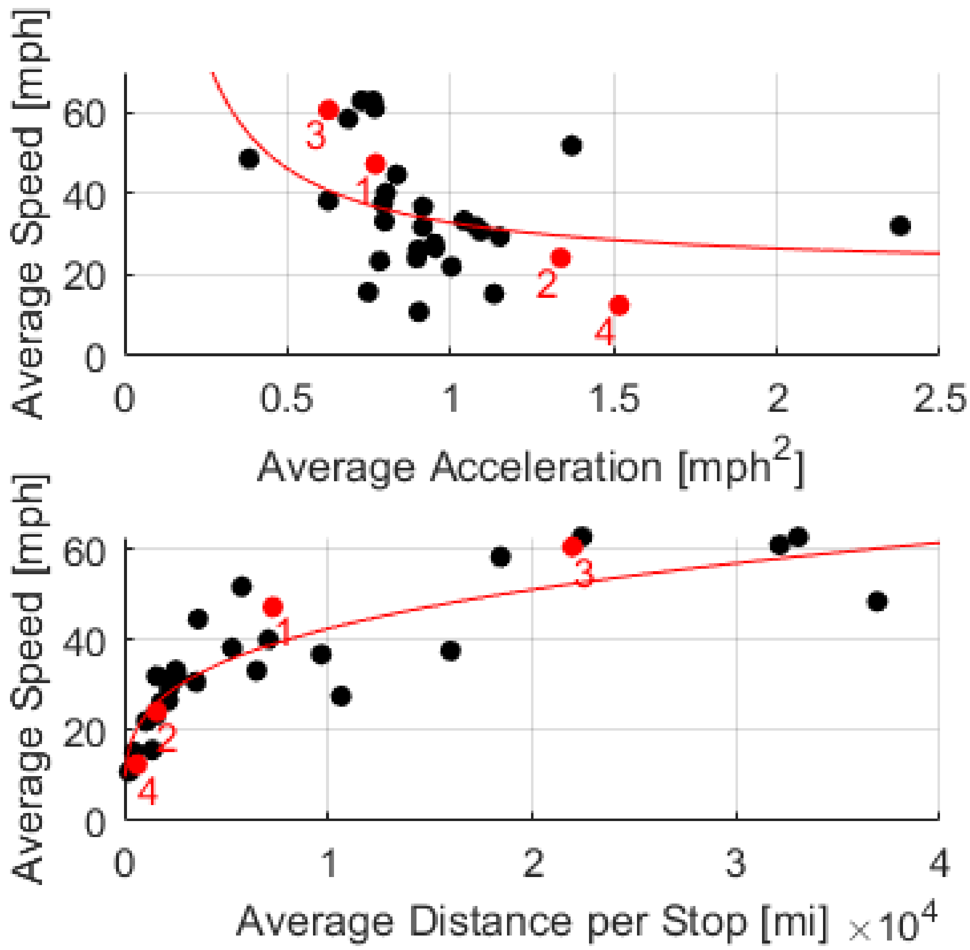

Figure 47: Found Clusters [72]

Afterwards a neural network will be used, containing the same inputs as the clustering algorithm, to help identify, which driving situation is currently occurring. Future work needs to be done implementing this and feeding it with drive cycle data similar to the use cases of the developed vehicle.

8.3 Summary

As the competition is going into Year 2 the control system has to be implemented and functional until May 2020. The model has to be further developed taking into account, diagnostics methods, fault mitigation and system safety. It aims to bring the theoretical work done into the actual vehicle facing excessive SIL and HIL testing. This includes developing software, validating plant models and closing gaps like the Driving Situation Identifier.

9 Conclusion

Facing CAFE fuel economy restriction and a shift in transportation needs towards car-sharing application, a mild-hybrid P4-P0 Parallel-through-the-Road HEV architecture is presented. The vehicle shall be used to fulfill the transportation needs occurring in the GTHA. It targets "Millennials" because that socioeconomic group is most likely to use this vehicle. The architecture consists out of a 1.5L engine together with 12V BAS motor and an electrified rear axle with a power oriented EM and HV battery pack.

A MIL model was set up to allow fuel economy and performance evaluation. The model development process considered plant models, controller models and driver models. Necessary energy management algorithms were developed and implemented. Novelty in the developed energy management algorithms are the application and modification of commonly used approach on the selected architecture. On the hardware side, each necessary controller was chosen, and a serial data architecture was defined. Fuel economy improvement up to 11% can be expected while ensuring that performance targets are similar to the stock vehicle.

In conclusion, the developed control system is ready to be implemented in future years. Novelty was achieved by utilizing two different voltage levels for propelling and the adaptive control strategy. In that way, fuel efficiency was maximized within the architectures and nearly optimal control is ensured for different occurring driving situations. The team should be adequately prepared and confident to realize the control system within the next years of the competition.

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