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DEVELOPMENT OF HYBRID SUPERVISORY CONTROLLER AND ENERGY MANAGEMENT STRATEGY FOR P2 PHEV

by

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1 Introduction

The powertrain of a parallel hybrid electric vehicle (PHEV) is a hybrid system with engine and electric motor powertrain systems, which provides an opportunity for energy management. Compared to the conventional vehicle, hybrid electric vehicles with high voltage battery and internal combustion engine have more complicated powertrain systems and ECUs, therefore, control system also becomes more complex. Under a hybrid supervisory controller (HSC), the power requested by driver is strategically distributed between engine and electric motor, and the distribution of driver requested power is supervised by energy management system which is the key technologies of PHEV.

This thesis discusses the development and implementation of hybrid supervisory controller for Wayne State University EcoCAR 3 clutch-less pre-transmission (P2) parallel PHEV, and an optimization based control strategy was proposed to reduce the energy consumption of PHEV.

1.1 The EcoCAR3 Competition

The EcoCAR 3 project is a four-year competition sponsored by General Motors and the U.S. Department of Energy challenging 16 universities teams to reengineer a 2016 Chevrolet Camaro to be a performance plug-in hybrid electric vehicle. A pre-transmission (P2) without clutch parallel architecture was chosen by Wayne State University EcoCAR3 team in Year 3.

The final objectives of this competition are to reduce energy consumption, greenhouse gas (GHG) emissions, criteria (regulated) emissions, and petroleum energy use (PEU), while to maintain the safety, drivability, performance and acceptability. In Year 3 of EcoCAR 3, WSU EcoCAR 3 controls team developed the supervisory control system based on our architecture and validated control strategies implemented on HSC under Model in the Loop (MIL), Software in the Loop (SIL) and Hardware in the Loop (HIL) by using dSPACE, and ultimately validate control strategies in the vehicle.

1.2 Wayne State University EcoCAR 3 Architecture

The Wayne State EcoCAR 3 team chooses the clutch-less pre-transmission parallel PHEV in Year 3. In P2 architecture, two powertrain systems are presented with a 2.4L LEA engine from GM running on E85, and a GKN AF-130 electric motor, controlled by a RMS PM150DX inverter. Coupled in line an 8L45 8-speed automatic transmission from GM is presented, In the trunk, a Bosch 10.7 kWh battery pack consisting of 8 Li-Ion modules as well as a BRUSA On-Board charger are also equipped to provide electric energy to drive the vehicle. The clutch-less P2 parallel powertrain system is shown in Figure 1.

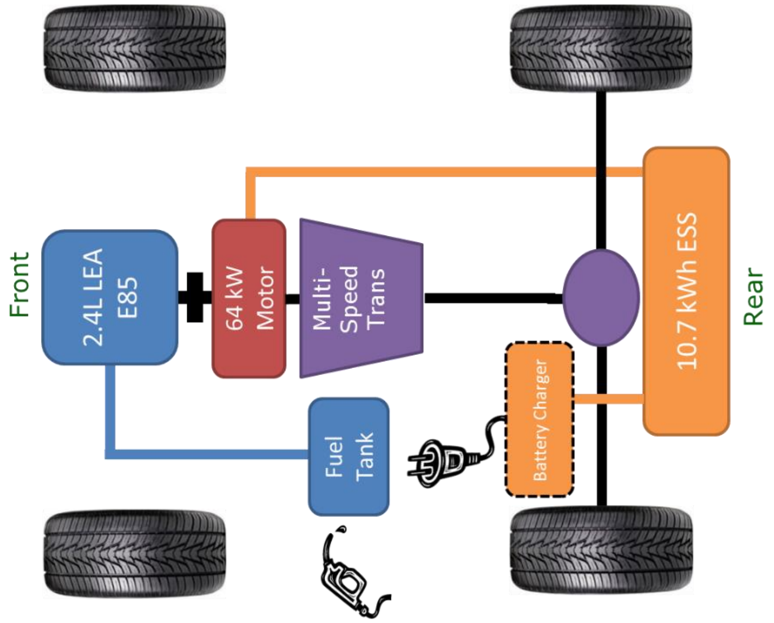


Figure 1 Powertrain Configuration of Clutch-less P2 PHEV

In this configuration, the clutch between engine and electric motor was remove compared to normal P2 architecture, instead, a coupler was placed to mechanically connect engine with electric motor. The WSU PHEV was required to have a total range over 150 miles, and four operational modes, which includes blended charge depleting mode, charge sustaining mode, sports mode and engine only mode. The controls development of PHEV is discussed in detail in chapter 4.

Figure 2 shows the WSU EcoCAR 3 control system structure, driver sends torque request to hybrid supervisory controller (HSC) which is responsible for managing driver commands as well as requested signals from hybrid component systems, and it also serves as gateway between stock vehicle CAN and team added CAN networks. The HSC then optimally distributed the torque request between engine and electric motor and sent command signals to individual controller modules, as shown in figure 2.

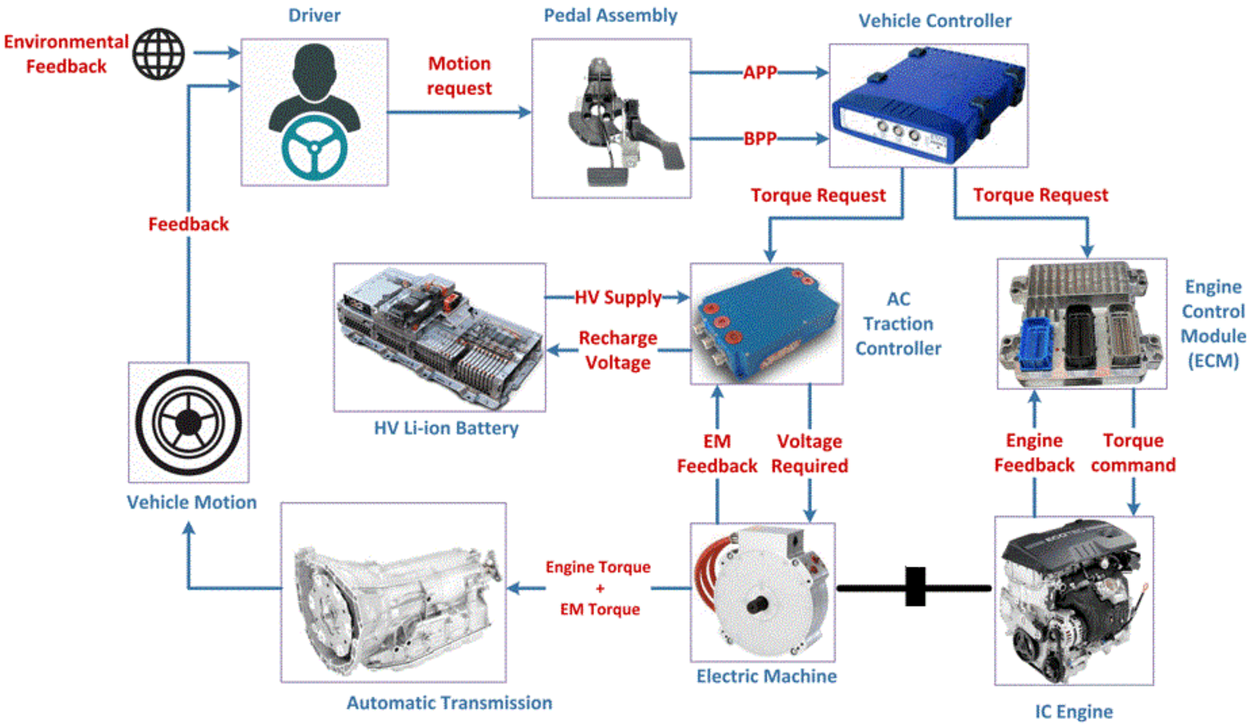


Figure 2 Control System Architecture

1.3 Outline of Thesis

In Year3, the hybrid powertrain system was fully integrated into the vehicle, and component controls and testing were also conducted to meet the requirements of competition. In addition, the hybrid vehicle model including engine, motor, battery, etc. was also developed by controls team in Simulink/Stateflow to test the algorithms needed to control the hybrid electric vehicle. This thesis aims to detail the development of a hybrid supervisory controller for WSU PHEV, including controls requirements, system diagnostics, operational modes and torque distribution strategies. Those controls algorithms are discussed in detail in chapter 4.

The thesis work mainly focus on two aspects of development of hybrid supervisory controller: torque distribution strategies and validation, fault detection and mitigation development. Chapter 2 discusses the literature review which includes the methods and strategies for developing hybrid supervisory controller as well as energy management strategies developed and implemented in current PHEV. Chapter 3 details the controls requirements and WSU EcoCAR 3 team HSC software structure. Chapter 4 details the development of hybrid supervisory controller, including fault detection and mitigation strategies implemented on HSC, torque control strategies within each operational mode and validation for control strategies under Model in the Loop (MIL) as well as Software in the Loop (SIL).

Another goal of this thesis is to propose a new energy management strategy which supervisors two powertrain systems and distributes power between engine and electric motor more efficiently. In chapter 5, a more detailed energy management strategy is discussed, and energy consumption is also conducted based on new control strategy as well as validation results. Chapter 6 discusses the conclusion and future work needs to be done for WSU EcoCAR 3 team.

2 Background and Literature Review

2.1 Introduction

This chapter provides background information for the hybrid electric vehicle architecture and the development of hybrid supervisory controller as well as energy management strategies for PHEV.

2.2 Parallel Hybrid Electric Vehicle Architecture

The Hybrid electric vehicles have two types of energy sources, electricity and fuel. Fuel represents that a fuel tank is required for internal combustion engine (ICE) to produce mechanical power, and electricity represents that a high voltage battery system is required to store the energy, and a traction motor will be used to produce mechanical power as well.

The parallel hybrid electric vehicles allow both engine and electric motor to deliver torque to drive the wheels, and traction power may be produced by ICE only, by electric motor only or by both ICE and motor. Since both engine and electric motor are coupled to the driveline of the wheels by clutch, and electric motor can function as generator to charge the high voltage battery by regenerative braking or taking the power from engine when its output power is greater than driver requested power. Figure 3 shows the configuration of general parallel hybrid powertrain system.

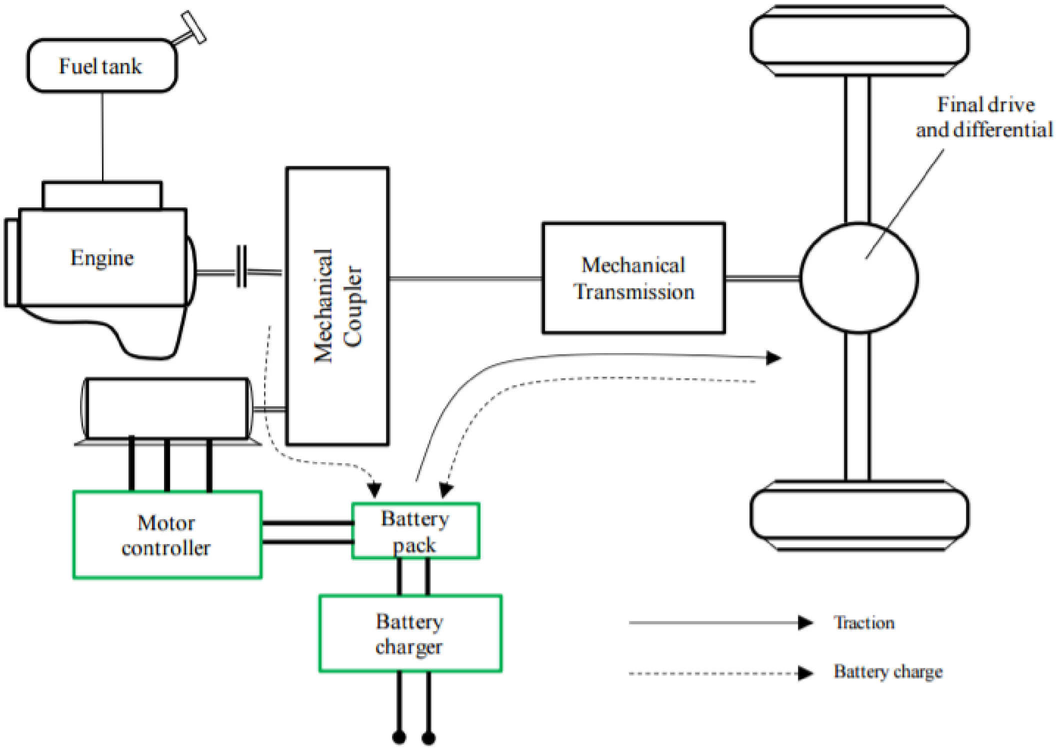


Figure 3 General Configuration of a Parallel Hybrid Drivetrain [1]

In parallel hybrid powertrain, there are two kinds of mechanical coupling: torque coupling and speed coupling. Torque coupling can add the torque of engine and electric motor together and deliver the total torque to the wheels. The advantages of torque coupling are that the engine and motor can be controlled independently but the speed of engine and motor cannot be controlled independently due to the fixed relationship between them. In speed coupling, the speed of engine and electric motor can be added together and torques are linked together [2].

More specifically, hybrid powertrain has different implementation of parallel architectures, depending on the placement of motor, there are five different architectures which are corresponding to the placement of the motor in the system [3], as illustrated in figure 4, including P0, P1, P2, P3, P4.

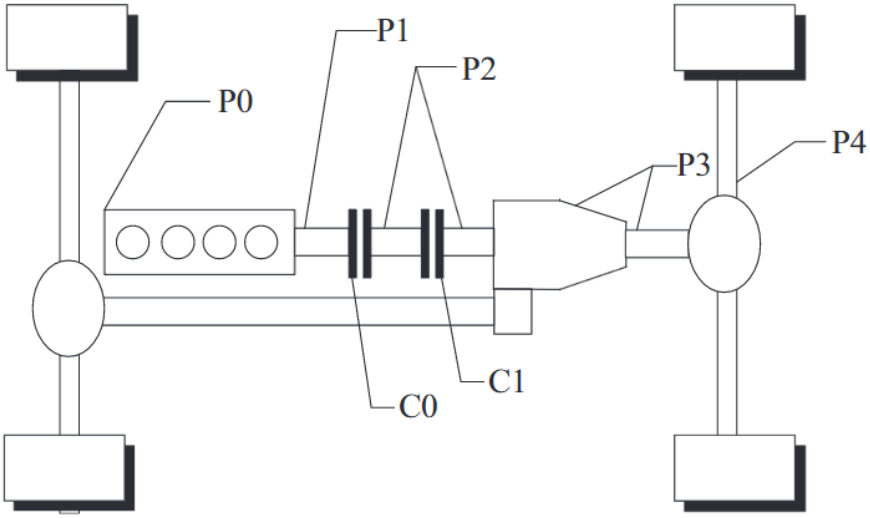


Figure 4Configurations of Parallel HEV [4]

As shown in the figure 4 above, P0 configuration represents that motor is located at the input to the engine, and P1 represents motor is located at the output of the engine, in which engine and motor can be isolated from the transmission by a clutch C0, P2 represents motor is located between the engine and transmission, P3 represents motor is located at the transmission and P4 represents that motor is mounted on axle. C0 and C1 are clutches.

2.3 Control System Design for PHEV

In hybrid electric vehicles, there are multiple torque sources (engine and electric motors) to generate mechanical energy required to drive the vehicle. Compared to conventional vehicles with single torque source and simple control systems, hybrid electric vehicles have more complicated control systems, which is properly manage the energy of two torque sources. The key function of control system in HEVs is energy management, the strategy of energy management is to optimally distribute the power between engine and electric motor to meet the driver requested power while to reduce energy consumption and emissions. There are two levels of control system in HEVs, supervisory control and component level control, the main functions of supervisory controller are to distribute torque to different torque sources and determine status of each component controller and subsystem/component (detect faults and failures). While component controllers, which contain main functionalities of physical components, receive command signals from supervisory controller as well as generate command signals to control actuators. Figure 5 shows the interconnecting scheme along with supervisory controller and ECUs.

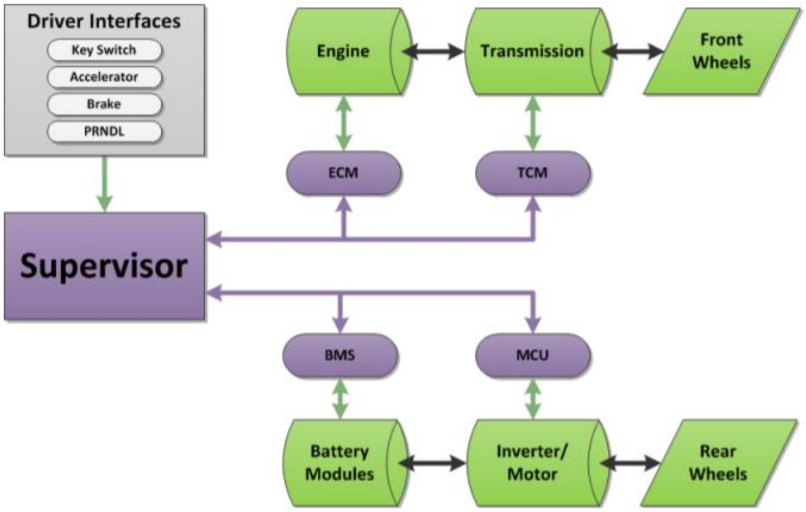


Figure 5 Parallel Control System

2.3.1 Component control level

In HEVs, the number of electronic control units (ECUs) need to control various aspects of vehicle and a typical car on the road today have from 40 to 100 microcontrollers [5], those controllers are used to control powertrain components, chassis, etc.

Component controllers consist of engine control module (ECM), motor control module (MCU), battery management system (BMS), transmission control module (TCM) and other regular controller modules in conventional vehicles. Component controllers interact with other control modules via Control Area Network (CAN), and receive command signals from supervisory controllers or other component controllers to meet the driver requirements [2]. Therefore, for each individual component controller, they are also responsible for controlling their corresponding actuators, like battery and engine, etc. and request responses are reported to supervisory controller which in turn makes the control decision.

2.3.2 Hybrid supervisory control level

The supervisory controller is considered to be the key part of the HEV control system, which provides high level management among all other controllers. HSC takes and processes all important signals from the other lower level controllers including Motor Control Module (MCU), Battery Management system (BMS), etc. and it also receives driver intended signals like accelerator pedal position (APP), key position and brake pedal position (BPP), as shown in figure 5, to make decisions for final execution [6].

The supervisory controller is to include the following functions: determine the status of each controller and subsystem/component, interpret driver inputs and determine how and to what degree requests can be fulfilled and oversee the startup and shutdown of the vehicle.

Improving energy efficiency is also a goal of supervisory controller, this is accomplished through optimizing the control strategy of distributing torque between engine and electric motors, energy management strategy maintains the vehicle at its highest efficient operating point and coordinates the status of engine, motor, battery, like State of Charge (SoC), temperature, etc. For instance, multiple operation modes in HEV like charge sustaining mode, regenerative braking mode are able to reduce fuel consumption as well as emissions.

2.4 Energy management strategy for PHEV

In the conventional vehicles, there is no need for energy management system, since only one torque source is presented in the vehicle and driver can deliver the power instantly by accelerator pedal position and brake pedal position. However, in hybrid electric vehicles, energy management system is necessary to be taken since vehicle doesn’t have idea that how much torque can be delivered by electric motor or engine. Due to the complicated structure of PHEVs, the design of control strategies is a challenging task. A lot of research has been carried out in this field. The main objective energy management strategy in hybrid electric vehicles is to minimize the energy consumption over a defined drive cycle and satisfy driver’s power demand with optimum vehicle performance. However, fuel economy and emission minimization are conflicting problems, a smart energy management strategy is used to satisfy trade-off between them [7].

Various control strategies are proposed to manage the energy between multiple energy sources, many researchers [8-11] have devoted their attention to the design and implementation of energy management strategy in HEVs. The energy management strategy can be mainly categorized in two types [12]: ruled-based strategy and optimization -based strategies. Rule-based control strategy is fundamental and robust control scheme that depends on the mode of operation [7], while in optimization based control strategies, the goal of this strategy is to minimize the cost function to find local or global optimization.

2.4.1 Rule-based Energy Management Strategy

The rule-based control strategies are fundamental and robust scheme that depends on the operation modes of vehicle, this control strategy can be easily implemented in real time to manage the power flow in hybrid electric powertrain, and rules are mostly defined by intuition, mathematical model or heuristic and generally without prior knowledge of drive cycle. Although these control strategies are robust and computationally efficient which can provide significant energy economy, they cannot guarantee the optimal performance of the vehicle in all situations and do not involve explicit minimization. Rule-based control strategy can be further divided into deterministic rule-based and fuzzy rule-based [13-14].

In deterministic rule-based control, it includes power follower control, state machine based control and on/off control. The deterministic rule-based control strategies are designed with the aid of engine operating maps, power flows within the powertrain and driving experience [7].

In the state machine based control, the transition between states is usually based on driver torque demand, vehicle speed, and status of hybrid powertrain systems as well as battery SOC, this part of control strategy is discussed in detail in chapter 4. However, this control strategy is unable to find the optimal torque distribution between engine and electric motor and require a lot of calibration.

2.4.2 Optimization-based Energy Management Strategy

As mentioned previously, the energy management strategy aims to determine the optimal power split between the engine and electric motor. In optimization based energy management strategy, the strategies tend to minimize the cost function, the cost function includes minimization of energy consumption, emission, etc.

There are two types of optimization based energy management strategy: global optimization and real time optimization [15]. Global optimization is also numerical optimization method, like dynamics programming [16], genetic algorithms [17], simulated annealing [18], the global optimal solution is calculated numerically by minimization of a cost function over a fixed drive cycle.

The real-time optimization, on the other hand, uses analytical method to find local optimization which is closed to globally optimal solution. The Equivalent Consumption Minimization strategy (ECMS) [19,20] provides a real-time energy management of HEVs which consists in minimization at each time step of the optimization of a defined instantaneous cost function. This strategy is reviewed in detail in the next section.

2.4.2.1 Dynamic Programming

Dynamic Programming is a numerical method for solving multistage decision making problems [16]. The implementation of dynamic programming is capable of providing an optimal solution to the power split between engine and electric motor while maintaining the battery OSC in certain threshold, however, this control strategy is only implementable in simulation environment, since it requires the prior knowledge of drive cycle, like road condition, grade, driver style, etc. but dynamic programming can be used to formulate and tune actual controllers and develop rule based controls [7].

Since the main drawbacks of the DP are computationally intensive and not implementable in real time, a ruled-based control combined with DP is presented [21], researchers derived rules from DP solutions to obtain near-optimal solution, this strategy not only makes it possible to calibrate the rule-based controller but also gives the near optimal solution in the real driving situation.

2.4.2.2 Equivalent consumption minimization strategies (ECMS)

Equivalent consumption minimization strategy is real time optimization method, which provides an effective solution for energy management problems in HEVs. ECMS calculates the instantaneous fuel consumption at each time step in the drive cycle, and it does not require prior knowledge of drive cycle [19].

In charge sustaining hybrid vehicles, high voltage battery is used as energy buffer since the state of charge of the battery in this mode maintains under a certain threshold, this means all electric energy comes from fuel and battery can be seen as reversible tank. Any electric energy used in discharge of the battery will be replenished from fuel in the future or from regenerative braking.

The core principle of ECMS is the equivalent cost vale that is assigned to the electric energy, this value represents the use of electrical energy used is equivalent to using a certain amount of fuel [15]. As shown in figure 6.

Figure X shows the energy path during the discharge and charge phase in parallel PHEV. In discharge phase, the electric motor provides the mechanical energy and the energy used in this phase will be replenished from the fuel tank. In charge phase, the electric motor acts as generator to charge the battery by engine, the dotted line shows that the energy charged by the engine will provide mechanical energy to save the fuel [15].

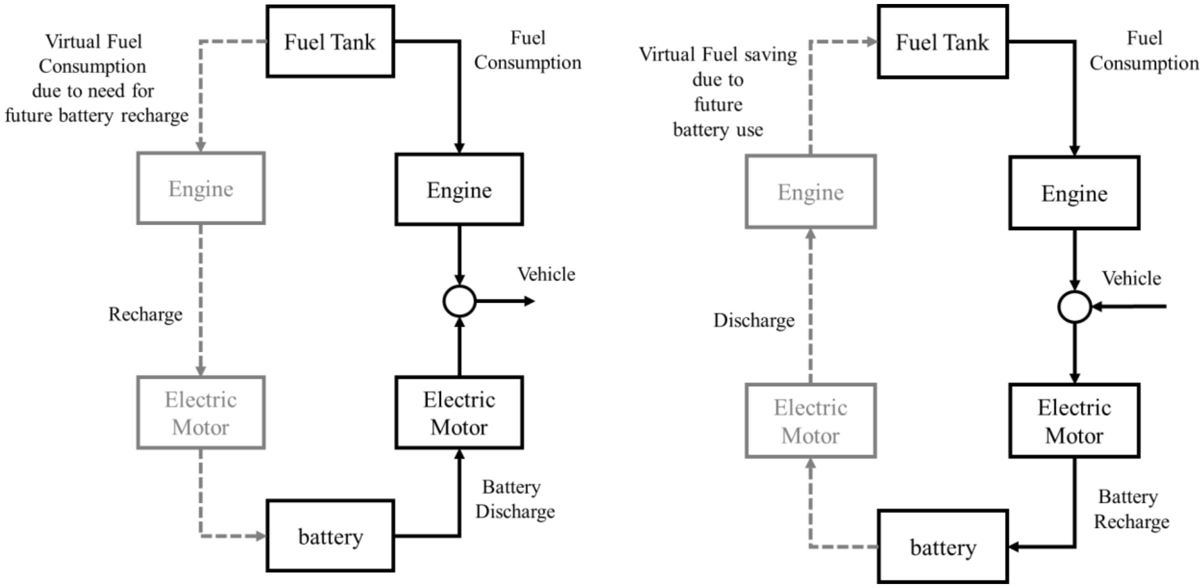


Figure 6 Energy path during discharge and charge for Parallel PHEV [15]

2.5 Literature Review

The paper written by Yatsko [22] presents the development and validation of control system for hybrid electric vehicle, the paper discusses the hybrid supervisory control development and validation, fault detection and mitigation, as well as energy management strategy. The hybrid supervisory control strategy developed in this paper is divided into three parts: vehicle mode selection, torque distribution or energy management, tactical control logic which includes regenerative braking, transmission shifting. A more detailed fault detection and mitigation strategy is presented to prevent critical failures occurring during the normal vehicle operation, the overall mitigation strategy mainly includes four operation modes: normal operation, power limiting, disable operating modes and shutdown vehicle, which are used to maintain safe vehicle operation.

Crain [23] emphasis the control system development and validation process to meet the vehicle technical requirements (VTS), this paper presents the overall software structure for supervisory controller, which contains inputs conversion, diagnostics, mode selection, component control and output conversions. The control strategy is also discussed by outlining CD and CS modes as well as additional modes in mode selection block. In addition to supervisory controller, the paper also presents electrical powertrain hardware and ICE powertrain hardware. With control system implemented in the vehicle, some performance tests and validation are conducted under SIL and HIL.

Harries and Brian Neal [24] demonstrates the development and validation for supervisory controller and power management control algorithm is also discussed to control the vehicle during charge sustaining operation. The paper first implemented a simplified bang-bang controller to operate at global minimum BSFC for engine and then a power tracking controller is proposed to reduce the energy consumption on simulated drive cycle. Two control strategies proposed in the paper are tested and compared under SIL and power tracking controller achieved almost % reduction in fuel losses during EPA drive cycle.

Manning [25] detail the control strategy for charge sustaining mode and development of the controls for diagnostics for series-parallel PHEV. The charge sustaining control strategy proposed in the thesis accounts for a variety of system operating points and penalizes or rewards certain operating points for some vehicle status conditions, like battery SOC. The control strategies are tested under SIL and HIL to validate the effectiveness of control system in real vehicle.

Karmustaji [26] proposed a real-time optimization based power flow controller for energy consumption and emissions reduction for parallel PHEV, in this thesis, a basic power flow controller is presented as a baseline controller, and then two optimization based power flow controllers using shift schedule and shift logic are presented to find the appropriate power split between the ICE and EM to reduce the energy consumption as well as emissions, to compare the effectiveness of optimization based controller, the real time energy and emission minimization controllers are tested under city and highway drive cycles when compared to the basic power flow controller, and optimization based controllers effectively reduced the energy consumption.

In Bovee's [27] work, a new version of supervisory controller algorithm was presented and tested under SIL environment, dynamic control algorithms are developed for charge depleting and charge sustaining mode based on Equivalent Consumption Minimization Strategy (ECMS). The charge depleting strategy includes a simplified version of ECMS that was able to select the most efficient torque split between front and rear electric machines, while charge sustaining strategy contains a full version of ECMS with multiple maps that were optimized offline to split the torque between engine, front EM, and rear EM. The ECMS algorithm adapted in this paper is implemented offline so it doesn’t require large computation time and new version of supervisory controller strategy increase the al electric range and reduce UF weighted fuel consumption over the baseline control strategy.

The previous work greatly benefits the development of this study, in this study, a supervisory controller was developed to control the interaction between powertrain components for WSU EcoCAR3. A rule-based control and fault detection and mitigation strategy were also incorporated into the supervisory controller and validated under model in the loop environment. The development of fault detection and mitigation is included in the thesis scope,

To minimize the energy consumption, a real-time optimization based control strategy, which is different from offline optimization strategy in Bovee’s work, was developed to control the engine and electric motor. The idea of ECMS algorithm was highly adapted from the research of Tammer Basar, Antonio Bicchi [15]. However, a combination of rule-based control strategy based on ECMS is also proposed in the thesis.

3 Controls Requirements for Hybrid Supervisory Controller

3.1 Software Development Process

To effectively design a control system software, a software development process V-model is adopted by WSU EcoCAR3 controls team. This is a systematic way of progressing from requirements to final software, which defines steps necessary to successfully design, implement a validated control system, as shown in figure 7 below.

Controls requirements are the first step in the V-model, in the left side of V-model, system functions and requirements are defined, implemented in the software, and the right of V-model includes the validation and verification of control system. For instance, if a function was designed and implemented in the test/simulation phase, then before moving to the next step: software integration, the software needs to be checked if the software module works as expected for all combinations of inputs. In the final step of vehicle test, the software still needs to be checked against the requirements and functions defined in the designing phase.

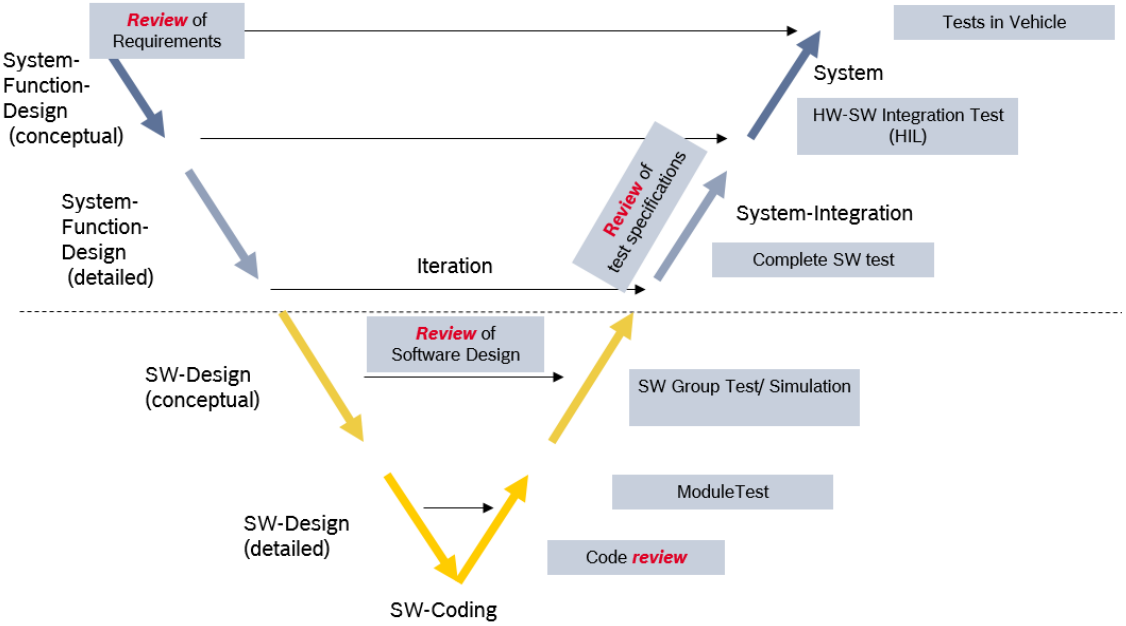


Figure 7 Software Development Process: V-Model

The V model is the key process in the development of hybrid supervisory controller. Figure 8 shows a detailed example of HSC development process.

In the function designing phase, the main function of hybrid supervisory controller can be divided into several sub-functions, including driver torque request, torque distribution, vehicle startup/shutdown, controller handshaking, etc. and then each sub-function is developed and implemented based on previous conceptual software design phase, finally the functions implemented in the module are tested under software in the loop (SIL), hardware in the loop (HIL) and vehicle in the loop (VIL) which is vehicle test.

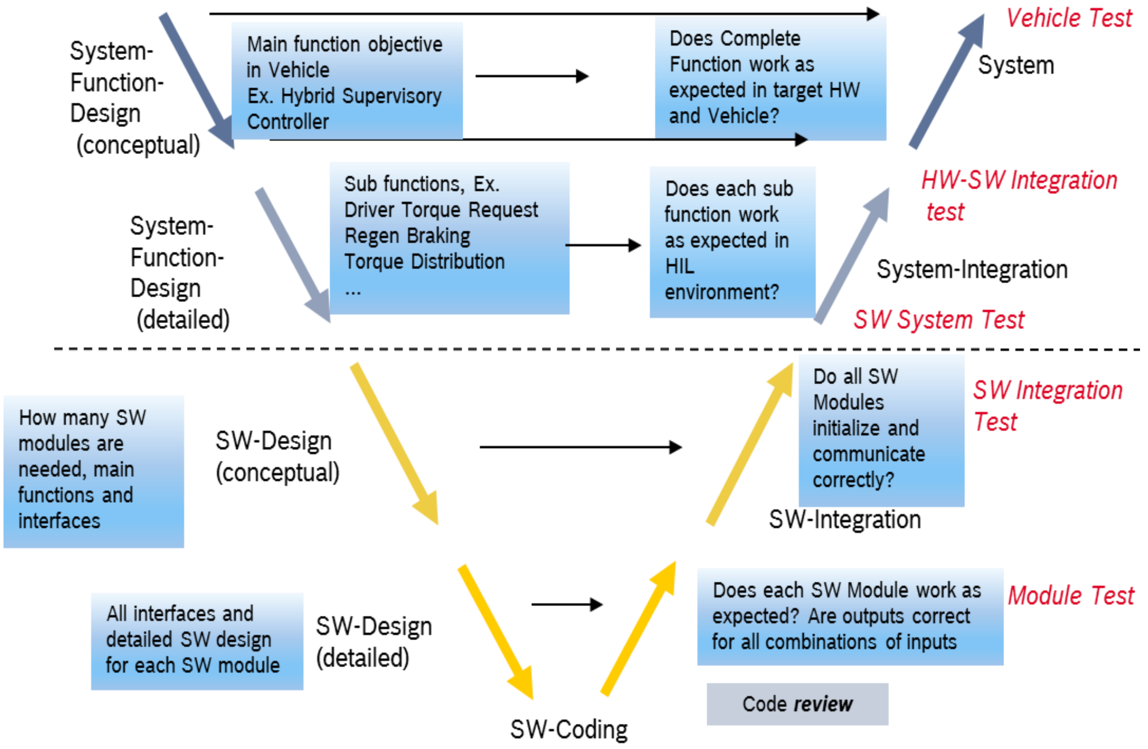


Figure 8 Hybrid Supervisory Controller Development Process

3.2 Controls Requirements

As mentioned in previous section, control requirements are the first step in the V-model. Following the development of control requirements, the control algorithms must be developed to satisfy the goal of initial design and VTS. The controls requirements can be derived from competition rules, hybrid powertrain functionality, vehicle technical specifications, etc.

There are different types of requirements, including requirements on controller input/output, functional requirements, diagnostic requirement as well as testing requirements. Control requirements can keep track of algorithms implemented in the code. Therefore, this requirement analysis can give the team a whole idea of what functionalities vehicle would need in the designing phase.

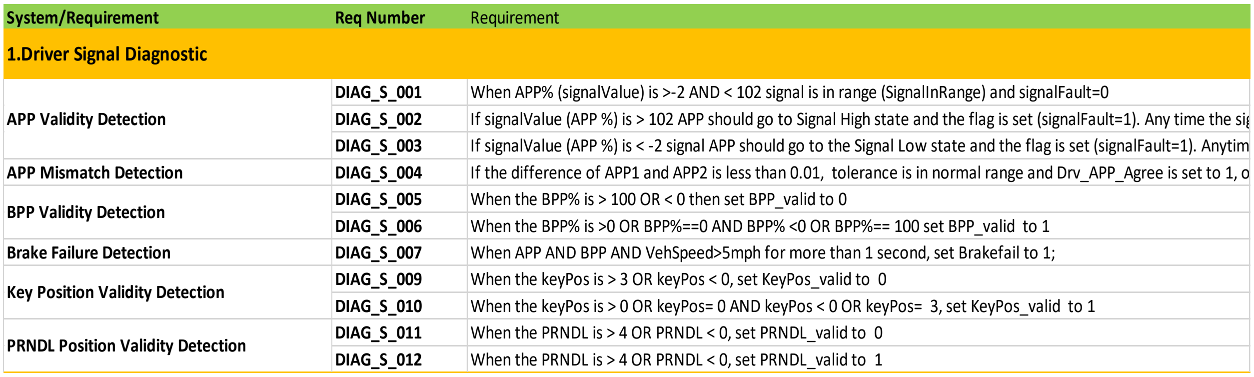
3.2.1 Controls Requirements for HSC

In Year 3, team needs to develop controller requirements that drive the development of activities in software. The control requirements can be divided into four levels: requirements on controller input/output, functional requirements, diagnostic requirement as well as testing requirements.

Requirements on HSC input/output include interfaces existed between the HSC and ECUs, like signals sent and received by HSC, and data type as well as name conversion are defined in the requirements.

The functional requirements for hybrid supervisory controller are to define how vehicle behaves and what functions vehicle needs to accomplish safe hybrid vehicle operation, including vehicle startup/shutdown, vehicle powertrain enabling, mode selection, torque distribution within each mode, thermal control system as well as regenerative braking behavior, etc. Each subsystem above involves lower level and detailed control requirements, for instance, requirements for thermal system control includes input/output to the thermal system, and functional requirements based on thermal system layout and goals of design.

Diagnostic requirements include three different level of diagnostic, component signal diagnostics, component functionality assessment, system level functionality assessments, figure 9 shows an example of requirements on signal diagnostic.



System/Requirement	Req Number	Requirement
1.Driver Signal Diagnostic		
APP Validity Detection	**DIAG_S_001**	When APP% (signalValue) is >-2 AND < 102 signal is in range (SignalInRange) and signalFault=0
	DIAG_S_002	If signalValue (APP %) is > 102 APP should go to Signal High state and the flag is set (signalFault=1). Any time the si
	DIAG_S_003	If signalValue (APP %) is < -2 signal APP should go to the Signal Low state and the flag is set (signalFault=1). Anytim
APP Mismatch Detection	**DIAG_S_004**	If the difference of APP1 and APP2 is less than 0.01, tolerance is in normal range and Drv_APP_Agree is set to 1, o
BPP Validity Detection	**DIAG_S_005**	When the BPP% is > 100 OR < 0 then set BPP_valid to 0
	DIAG_S_006	When the BPP% is >0 OR BPP%==0 AND BPP% <0 OR BPP%== 100 set BPP_valid to 1
Brake Failure Detection	**DIAG_S_007**	When APP AND BPP AND VehSpeed>5mph for more than 1 second, set Brakefail to 1;
Key Position Validity Detection	**DIAG_S_009**	When the keyPos is > 3 OR keyPos < 0, set KeyPos_valid to 0
	DIAG_S_010	When the keyPos is > 0 OR keyPos= 0 AND keyPos < 0 OR keyPos= 3, set KeyPos_valid to 1
PRNDL Position Validity Detection	**DIAG_S_011**	When the PRNDL is > 4 OR PRNDL < 0, set PRNDL_valid to 0
	DIAG_S_012	When the PRNDL is > 4 OR PRNDL < 0, set PRNDL_valid to 1

Figure 9 Requirements on signal diagnostics

Testing requirements include all critical functions implemented in the HSC that need to be tested, for instance, vehicle startup operation, PRNDL, etc. Table 1 list a sample of vehicle startup/enabling procedure requirements.

3.1 PRNDL			
3.1.1 *Park* The powertrain does not transmit any torque to the wheels or allow the vehicle to roll when PRNDL is in P	Vehicle speed=0	SIL/HIL/In vehicle	1. Start vehicle by turning key state to crank 2. Set PRNDL position to P 3. Set APP > 10% 4. Set BPP = 0%
3.1.2 *Reverse* The powertrain transmits only torque to the wheels that propel the vehicle in reverse when the PRNDL is in R	Vehicle speed<0	SIL/HIL/In vehicle	1. Start vehicle by turning key state to crank 2. Set PRNDL position to R 3. Set APP > 10% 4. Set BPP = 0%
3.1.3 *Neutral* The powertrain does not transmit any torque to the wheels when the PRNDL is in N	Vehicle speed=0	SIL/HIL/In vehicle	1. Start vehicle by turning key state to crank 2. Set PRNDL position to N 3. Set APP > 10% 4. Set BPP = 0%
3.1.3 *Drive* The powertrain transmits torque to the wheels to propel the vehicle forward when the PRNDL is in D	Vehicle speed>0	SIL/HIL/In vehicle	1. Start vehicle by turning key state to crank 2. Set PRNDL position to D 3. Set APP > 10% 4. Set BPP = 0%
3.2 Startup/Enabling Procedure			
3.2.1 *Vehicle in Park* The vehicle will not start if the PRNDL is not in P	Vehicle does not start (signal TBD)	SIL/HIL	1. Set PRNDL to D, R or N 2. Set APP=0% 3. Set BPP =100% 4. Turn key to crank

3.2.2 *Brake Pedal Depressed* The vehicle will not start if the brake pedal is not depressed a minimum of 10%	Vehicle does not start (signal TBD)	SIL/HIL	1. Set PRNDL to P 2. Set APP=0% 3. Set BPP =7% 4. Turn key to crank
3.2.3 *Accelerator Pedal Not Depressed* The vehicle will not start if the accelerator pedal is depressed more than 3%	Vehicle does not start (signal TBD)	SIL/HIL	1. Set PRNDL to P 2. Set APP=5% 3. Set BPP =100% 4. Turn key to crank

Table 1 Test Requirements for Vehicle Startup operation

4 Development of Hybrid Supervisory Controller

4.1 Introduction

The hybrid supervisory control is a high – level controller that interprets driver demand and controls interaction between powertrain components by their respective control units, it typically sends out analog, digital and CAN signals to sub-controllers to fulfill torque or speed request from engine or motor, and determine the appropriate torque split between two components as well as correct operating mode for hybrid electric vehicle. In addition, the key functions of HSC include energy management strategy and fault detection and mitigation which assess the status of hybrid powertrain components. The HSC mainly interacts with different components control modules including engine control module, transmission control module, battery management system, body control module, motor control module.

The HSC is primarily divided into four parts, the first part is driver requested torque, usually this part calculates the torque required at the wheels based on accelerator pedal position or brake pedal position and vehicle speed, which is the key input to the torque distribution. The second part is mode selection and torque distribution, the propulsive torque split strategies will be explored in next section, the last part is fault diagnostics which assess the status of signals, powertrain as well as system level, it's derived from team's DFMEA (Appendix A.1)

4.2 Hybrid Supervisory Controller Software Structure

The hybrid supervisory controller takes different kinds of signals including analog, digital and CAN signals, which are transmitted through team added high speed GM CAN networks. The signals coming from lower level component controllers are then fed into main HSC functions which is illustrated in figure 10. The output signals from hybrid supervisory controller are mostly control signals to component control module, such as engine torque demand, motor torque demand, etc. Those signals which are required by vehicle will be separated into messages needed by individual controllers. It also includes signals required by stock vehicle.

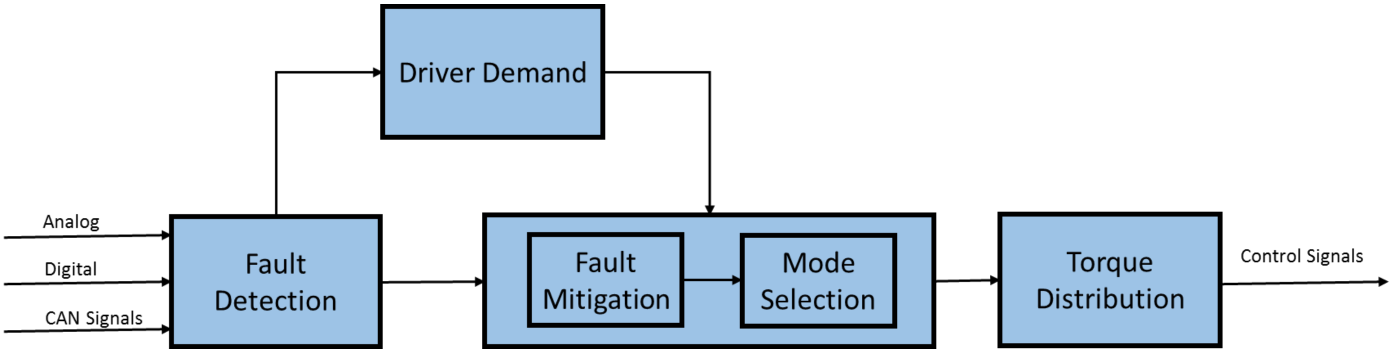


Figure 10 Hybrid Supervisory Controller Software Structure

As mentioned previously, the signals coming from lower level controllers will be fed into fault detection block which consists of three diagnostics levels including component signals diagnostics, component functionality assessment and system level diagnostics, the details in different level of diagnostics will be explored in the next sections. Signals from fault detection are then sent to driver demand block to determine drive requested torque based on APP or BPP as well as other signals such as vehicle speed, transmission ratio and vehicle mode, etc. Fault mitigation and mode selection block will take signals from fault detection to determine the available vehicle operating mode, and then torque distribution block will calculate command torque for engine and motor. There are also other functions in the HSC, such as regenerative braking behavior, vehicle startup and shutdown.

4.3 Diagnostic Development

Fault Diagnosis algorithm contains fault detection and mitigation strategies for safety critical systems which is derived from the team performed DFMEA (Appendix A.1). Fault detection algorithm identifies and detects possible failures and faults of powertrain components, which is accomplished by receiving signals from component controllers, and fault mitigation algorithm takes actions that would need to mitigate faults for safety concern. DFMEA documentation defines each item or function in the vehicle that should be examined for any potential failures, potential failures are discussed to estimate how often the fault occurs and the severity level of failure as well as the possibility of detection. The DFMEA also documents the detection and mitigation strategies to verity and validate that failure can be managed under safe operation. The failures with high RPN numbers are discussed in the next section and safety requirements of HSC are derived from DFMEA based on RPN numbers in Appendix. Table 2 below shows the safety requirements for critical functions in the HSC.

Table 2 Critical Safety Requirements for HSC

Control Unit	Safety Functions
Vehicle Hybrid Supervisory Controller (HSC)	The HSC should monitor the actual accelerate pedal position and brake pedal position
	The HSC should monitor the actual torque of EM against the request torque
	The HSC should monitor the actual torque of engine against the request torque
	The HSC should monitor the transmission rotation direction against the gear position
	The HSC should monitor 12V power supply
	The HSC should monitor the actual gear position
	The HSC should monitor the engine speed against electric motor speed.
	The HSC should monitor High voltage battery limit
	The HSC should monitor engine temperature and motor temperature against their maximum and minimum.
	The HSC should monitor the CAN communication for each controller

4.3.1 Fault Detection Strategy

Fault detection strategy only detects the faults or failures for each powertrain components as well as system level. The fault detection strategy is organized by three different levels, including signal diagnostics, component diagnostic and system level diagnostics. Each part provides different level functionality assessments. For instance, Signal diagnostics is mainly to assess signals coming from each powertrain controller module to check validity of data or whether signals are out of safe range, and the results of signal diagnostics will be assessed to determine each component’s current level of functionality in the component diagnostics, eventually previous results will go to system diagnostics to determine the overall functionality of entire powertrain. The fault detection algorithm structure is presented in figure 11.

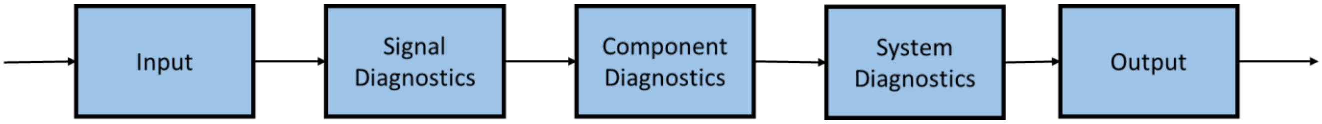


Figure 11 Fault Detection Strategy

There are several different techniques for detecting faults, the fault detection strategies implemented by EcoCAR3 team are mainly threshold techniques, which are easiest fault diagnosis to implement. The threshold technique is to set certain limit or threshold for signals that need to be monitored, if one of these signal values go outside the threshold which means something is wrong. This technique is widely used for monitoring component temperature, speed or high voltage and current. The validation in SIL environment for fault detection strategy will be explored explicitly in the next section.

4.3.2 Fault Mitigation Strategy

Fault mitigation strategy is directly related to fault detection and the function of fault mitigation is to maintain the safe operation of vehicle and try to avoid large deviation from driver's demand. Different faults would result in various mitigation strategies. Some faults will require vehicle operation to be stopped, some will change to limo mode, while some will simply result in the display of an indicator light on the user interface. In the HSC algorithm, vehicle operation is stopped when an accelerator pedal fault occurs. However, in the case of some faults, like ground fault detection, only a warning is presented depending on the value of the resistance drop between the high voltage bus and chassis ground. A table of diagnostics checks and remedial actions taken by HSC is shown in table 3. For other faults like overtemperature of battery or motor, it's possible that the action taken by the HSC to limit power or increase speed of cooling fan. An example of safety critical fault will be shown in section 4.3.3

Table 3 Diagnostic checks and remedial actions for safety critical functions

Requirements	Required condition (Detection Strategy)	Remedial Action if Conditions are not met
APP 1 Voltage in range	0.485V<=APP1<=2.17V	Shut off the vehicle
APP 2 Voltage in range	0.973V<=APP2<=4.27V	Shut off the vehicle
APP 1 and APP2 Agree	APP1 = APP2 ± 1%	Shut off the vehicle
BPP out of range	0<=BPP<=100%	Shut off the vehicle
Motor CAN	Fault occurs include overruns, timeouts, and data mismatch. Alive Rolling counter is used to determine if the component is still communicating on the CAN	Disable respective component
Engine CAN		
TCM CAN		
BCM CAN		
BMS CAN		

DC-DC CAN		
Engine Speed	Engine Speed<6500 RPM	Engine Torque Command=0
Engine Coolant Temperature	Engine Coolant Temp<100 $^{\circ}C$	Limit Engine Power
	Engine Coolant Temp<120 $^{\circ}C$	Disable Engine
Motor Speed	Motor Speed<8000 RPM	Disable motor
Motor Temperature	Motor Temp<150 $^{\circ}C$	Disable Motor
Battery Voltage	BattVolt<419V BattVolt>291V	Disable Inverter/Clear fault/Engine only mode
Battery Current	BattCurr<180V BattCurr>-315V	Disable HV battery
Battery Contactors	Contactor Status=Contactor Command	Disable HV battery
Battery SOC	SOC>10%	Disable HV battery
Battery Temperature	High range and low range BattTemp<30 $^{\circ}C$ BattTemp>0 $^{\circ}C$	Limit the HV battery power
	Critical range: BattTemp<55 $^{\circ}C$ BattTemp>-28 $^{\circ}C$	Disable Battery/Vehicle go to Engine only mode
Ground Fault Detection	Isolation Resistance/Battery Voltage>500 Ω / V	Illuminate the indicator
Power Electronics Coolant Temperature	Coolant tem sensor<45 $^{\circ}C$	Turn on fan, radiators
	Coolant tem sensor<65 $^{\circ}C$	Disable power electronics
Motor Torque Mismatch	Mismatch Degraded	MotTrqCmd decreases to 70% of commanded torque
	Mismatch Limphome	MotTrqCmd decreases to 30% of commanded torque
	Mismatch Critical	Disable Motor
Engine Torque Mismatch	Mismatch Degraded	EngTrqCmd decreases to 70% of commanded torque
	Mismatch Limphome	EngTrqCmd decreases to 30% of commanded torque
	Mismatch Critical	Disable Engine

4.3.3 Critical Fault Validated on the MIL/SIL

In this section, a full control system development for the specific fault scenario in WSU EcoCAR3 team is discussed, the process first starts by identifying safety requirement derived from DFMEA documentation for this specific fault, and then detection strategy and mitigation strategy are verified and validated for this fault under MIL/SIL.

4.3.3.1 Fault-Scenario Description

During the Year3 vehicle testing, a mechanical failure related to coupler occurred and the bolts connected the engine crankshaft with electric motor were broken for the first time, as shown in figure 12, figure 13 shows that all six bolts are sheared by the large torque requested from engine and electric motor, and they have the same intersecting surface, as shown in figure 13.

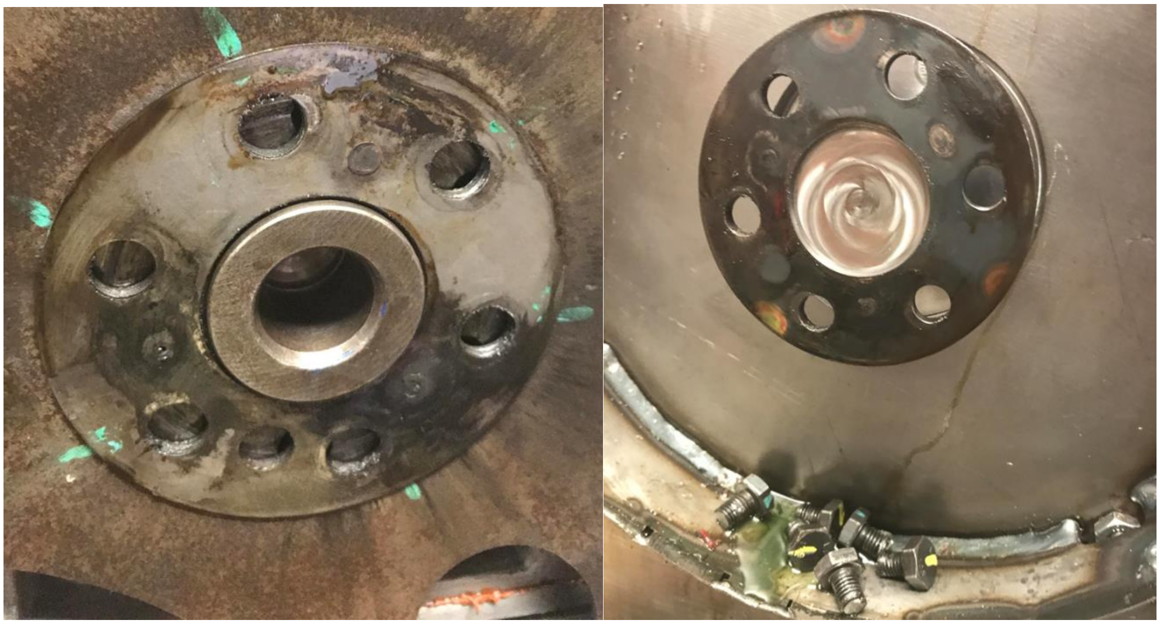


Figure 12 The engine crankshaft and coupler

Figure 13 Broken bolt

This fatal fault has been analyzed for several reasons, improper bolt specification is the main issue for this fault, however, based on the CAN log data which is derived from vehicle testing CAN messages, as shown in figure 14, it's clear that this fault actually occurred at the time when vehicle transitioned from CD mode to CS mode, which means that vehicle request too much torque at the beginning of engine charging mode since negative torque requested from motor increases the stress of mechanical connection between engine and electric motor.

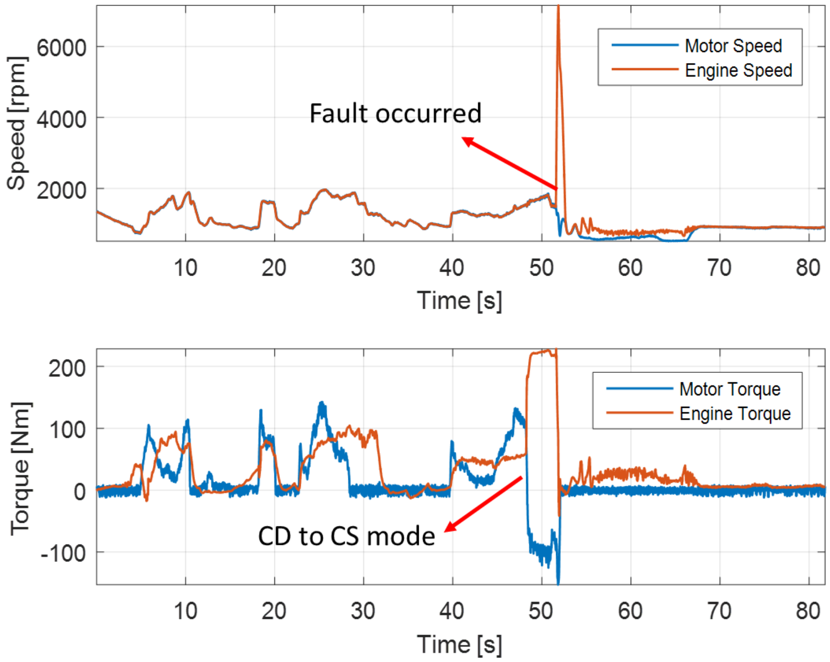
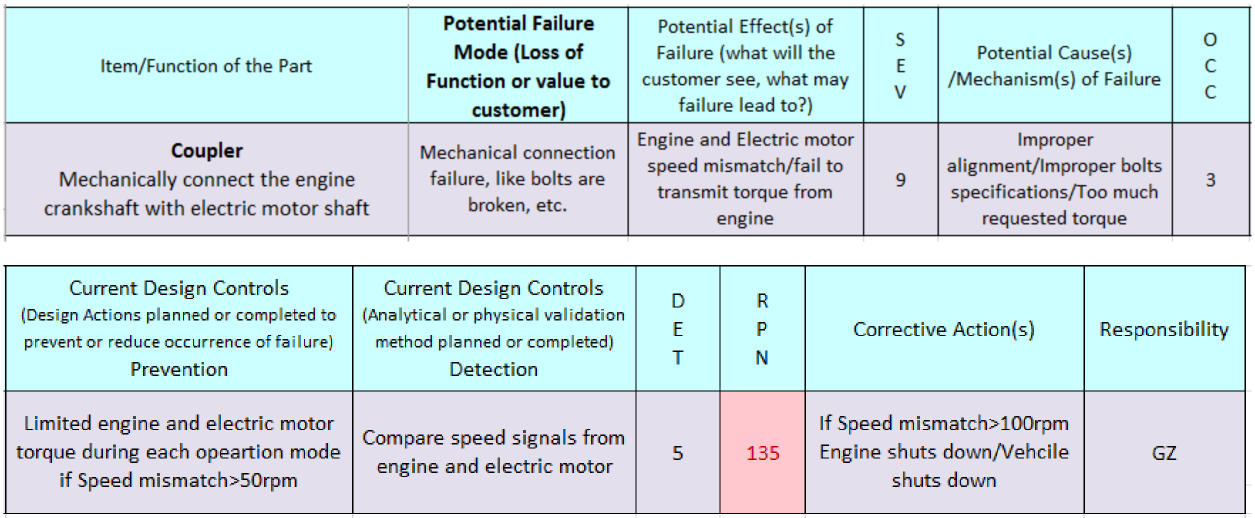


Figure 14 Engine and motor speed and feedback torque during fatal incident

4.3.3.2 Fault Diagnostic Strategy

In order to avoid this fatal fault in the future testing activity, the safety analysis is conducted for this specific fault scenario. The first step of safety analysis is to derive the safety requirement, which is the beginning of control system development process. The safety requirement can be derived from DFMEA, as shown in the following figures. Due to the limitation of clutch-less P2 parallel architecture, this fault can be specific scenario since mechanical failure to coupler between engine and electric motor can lead to undesired acceleration/deceleration, over speed of the engine or even the damage to the electric motor. Therefore, a robust fault detection and mitigation strategy for this fault can greatly decrease the occurrence of this fault and let vehicle operate in a safe mode when fault happens.



Item/Function of the Part	**Potential Failure Mode (Loss of Function or value to customer)**	Potential Effect(s) of Failure (what will the customer see, what may failure lead to?)	SEV	Potential Cause(s) /Mechanism(s) of Failure	OCC
Coupler Mechanically connect the engine crankshaft with electric motor shaft	Mechanical connection failure, like bolts are broken, etc.	Engine and Electric motor speed mismatch/fail to transmit torque from engine	9	Improper alignment/Improper bolts specifications/Too much requested torque	3

Current Design Controls (Design Actions planned or completed to prevent or reduce occurrence of failure) Prevention	Current Design Controls (Analytical or physical validation method planned or completed) Detection	DET	RPN	Corrective Action(s)	Responsibility
Limited engine and electric motor torque during each opeartion mode if Speed mismatch>50rpm	Compare speed signals from engine and electric motor	5	135	If Speed mismatch>100rpm Engine shuts down/Vehcile shuts down	GZ

Figure 15 DFMEA for the specific fault scenario

Fault Detection

The fault can be detected based on the comparison of engine speed and electric motor speed, as shown in CAN log data from vehicle testing, when fault happens, the difference of engine speed and motor speed can be over 1000 rpm, which indicates that the fault already occurred, therefore, a fault mitigation is taken in HSC to operate vehicle in a safe mode. The fault detection strategy can be divided into two levels: Degraded and Critical level.

Fault Mitigation

The goal of fault mitigation strategy is to maintain the safe vehicle functionality, if the speed mismatch fault is triggered, then the vehicle will shut down completely to avoid further damage to the motor or engine. In degraded level, the engine torque and electric motor commanded torque are limited during engine charging or regenerative braking mode.

Table 4 Fault Mitigation Strategy Overview

Requirements	**Condition**	**Preventing actions**
Normal Operation	Speed Mismatch< 50 rpm	No action taken
Limited Operation	50 rpm<Speed Mismatch<100 rpm	Reduce motor negative torque and engine torque by 50%;
Critical Operation	Speed Mismatch> 100 rpm	Shut down the vehicle;

4.3.3.3 Diagnostic Strategy Validation in MIL/SIL

Fault detection and mitigation strategy are implemented in the team's HSC to validate the effectiveness of the strategy under MIL/SIL environment by using Simulink. In WSU EcoCAR3 team's vehicle simulator, the fault is inserted in the engine plant model, and vehicle simulator is running under 505 drive cycle.

1) Degraded Level

In this level, once the difference of engine speed and electric motor speed is over 50 rpm, the engine torque and electric motor requested torque will be reduced by 50%, the fault insertion and fault detection are shown in figure 16.

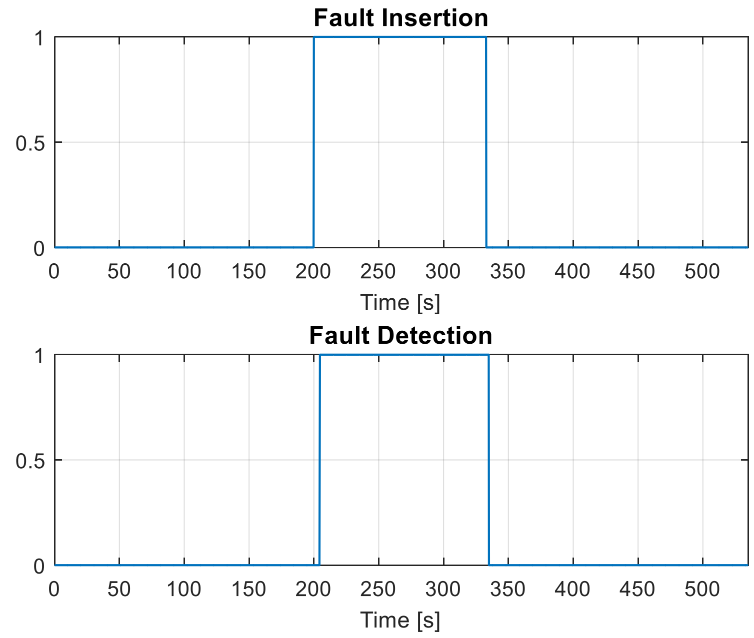


Figure 16 Fault Insertion and Fault Detection

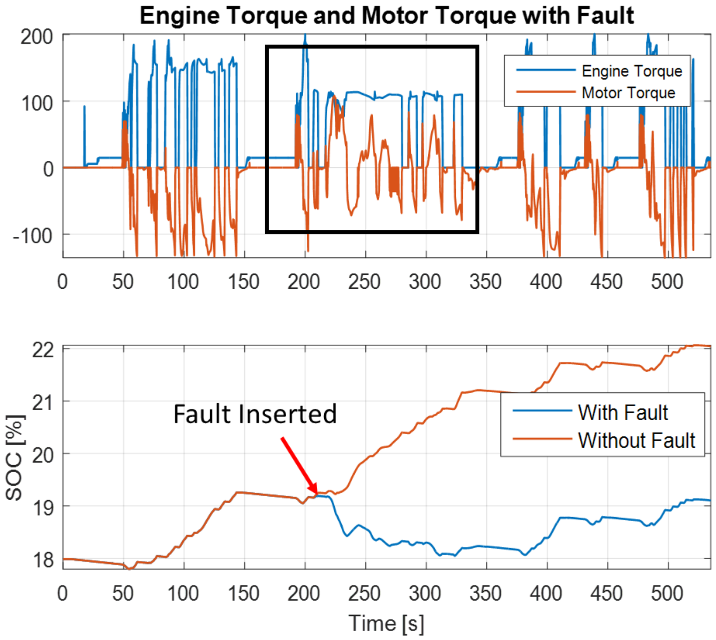


Figure 17 a) Engine and motor torque request; b) Battery SOC under fault scenario

Figure 17 above shows that at time of 200s, the fault was inserted to the system, the fault detection in the HSC detected the fault quickly and mitigation action is taken to limit the engine torque and electric motor torque in the HSC. Battery SOC wen down at the moment when the fault was detected and mitigated, since during the engine charging mode, the negative requested motor torque was limited, as shown in black rectangle in the figure 17. once there is no fault detected in the HSC, the vehicle goes to normal CS operation to keep sustain the SOC.

2) Critical Level

In the critical fault level, when the speed mismatch is over critical threshold, the vehicle will shut down completely to avoid further damage the engine or electric motor which may be caused by major failure.

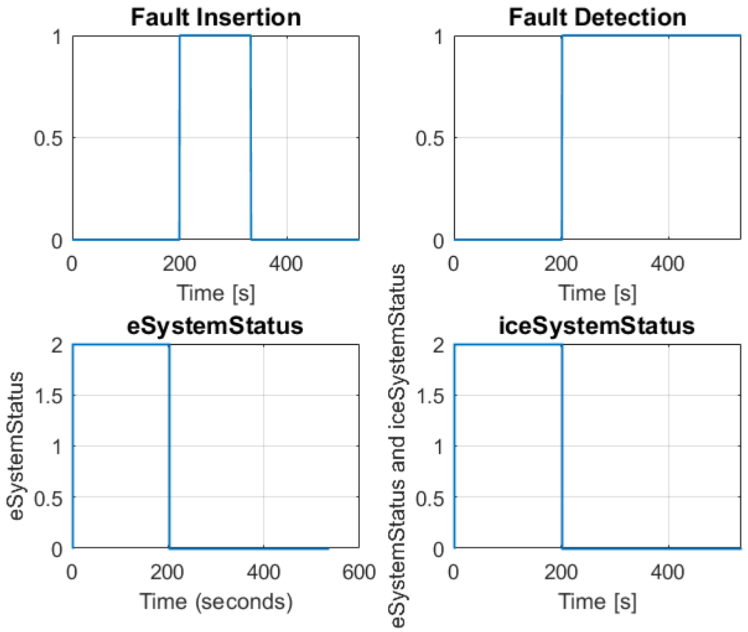


Figure 18 Fault Insertion, Detection, system level status

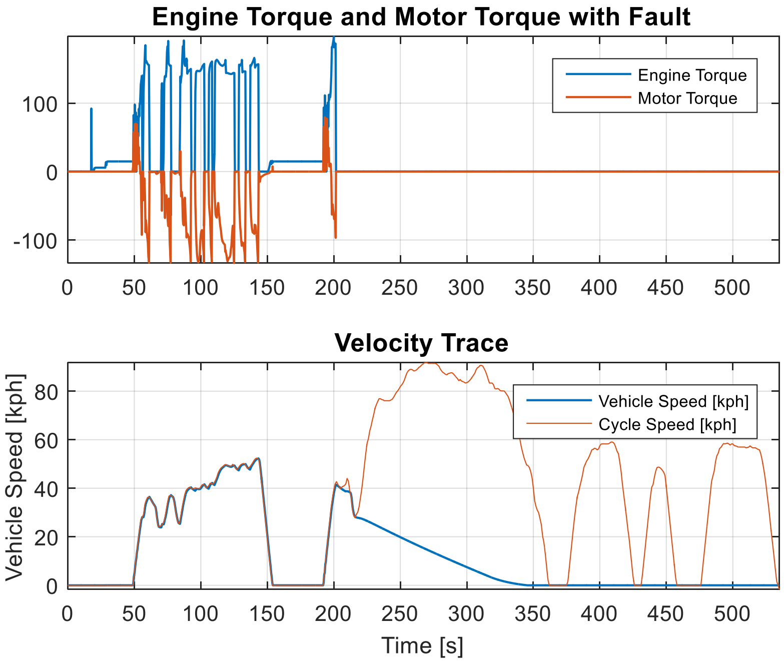


Figure 19 Engine torque and motor torque, speed trace

Figure 18 above shows that this critical fault is inserted at about 200s, and system level functionality status goes to offline when the fault is detected in the HSC. The results of fault detection are then passed to the torque distribution; the remedial action would be taken by HSC to determine the available modes of operation based on diagnostics. The plot figure 19 above shows that when fault occurs the vehicle will shut down and motor torque output will go to 0, since motor dynamics is not implemented in the plant model, the torque would be 0 immediately when fault occurs.

4.3.4 Test case Development

Test case is important document in the process of requirements and testing development, it documented procedure for performing verification and validation of supervisory controller. Test cases were executed for safety critical functions in the SIL/HIL environment and eventually in the vehicle, and the results of test executed by the control code will be compared to the expected results, and how supervisory controller respond to the fault scenarios and what remedial actions are taken would be defined in the document as well.

Test cases are detailed and step by step procedures to be followed to execute a specific test, for instance, during the development of diagnostics, test cases need to cover all safety-critical functions and fault scenarios, as explained in section 4.3.3, an engine and motor speed mismatch fault scenario needs to be considered and detected by fault detection algorithm in the supervisory controller.

Table 5 provides a summary of the safety critical tests to date. The tests developed in Year3 cover the faults which make ECUs or component unable to meet the driver demand, the results of tests executed by the control code will be compared to the expected results. Step-by-step procedures for test cases that have been developed for modeling and simulation provided in the Appendix.

Table 5 Safety Critical Function Testing Summary

Name and Description	**Pass/Fail Criteria**	**Primary Testing Environment**
3.1 Accelerator Pedal		
3.1.1 *Accelerator Pedal Signal Range* If any of the two accelerator pedal signal is out of range the vehicle receives only idle torque (limphome)	*APP > APPmax* APP Status = High Vehicle mode = Limphome mode	SIL/HIL
	APP <APPmin APP Status = Low Vehicle mode = Limphome mode	SIL/HIL
3.1.2 *Accelerator Pedal Mismatch* If the istantaneous value of the APP1 does not equal the value of APP2 within a +/- 1% the vehicle receives idle torque	APP Agree =0 Vehicle mode= Limphome mode	SIL/HIL
3.1.3 *Brake Pedal Signal Range* If the brake pedal signal is out of range vehicle shuts down	BPP Status = Out of range Vehicle mode = Shutdown	SIL/HIL
3.1.4 *Brake Pedal Signal Fault* *BPP depressed at a certain vaule but vehicle does not decelerate at expected rate*	BPP Status = Signal Fault Vehicle mode = Shutdown	SIL/HIL
3.2 PRNDL		
3.2.1 *Park* The powertrain does not transmit any torque to the wheels or allow the vehicle to roll when PRNDL is in P	Vehicle speed=0	SIL/HIL/In vehicle
3.1.2 *Reverse* The powertrain transmits only torque to the wheels that propel the vehicle in reverse when the PRNDL is in R	Vehicle speed<0	SIL/HIL/In vehicle

3.2.3 *Neutral* The powertrain does not transmit any torque to the wheels when the PRNDL is in N	Vehicle speed=0	SIL/HIL/In vehicle
3.2.3 *Drive* The powertrain transmits torque to the wheels to propel the vehicle forward when the PRNDL is in D	Vehicle speed>0	SIL/HIL/In vehicle
Powertrain Torque Control		
Torque Direction Fault The regenerative braking torque direction is incorrect when braking.	Motor torque output=0; the regenerative braking will be off.	SIL/HIL
Vehicle Direction Fault The vehicle does not move in the intended direction when in drive gear.	Vehicle mode = Shutdown	SIL/HIL

4.4 Mode Selection and Torque Split

The mode selection block takes signals from drive request and diagnostics block and contains two major functions: Choosing the mode of operation. The HSC was developed by using rule based control strategies, a set of rules were defined during the design phase, the mode selection block was modeled by Stateflow to represent vehicle operational modes, and transitions between those modes are pre-defined by a set of logical conditions and fault detection information from diagnostics block, for some safety critical faults, the current vehicle operational mode will be stopped if those faults occur, however, some faults will lead to limo mode to ensure the vehicle safe operation while meeting driver demands. The second major function is to find appropriate torque split between the engine and electric motor, the torque split calculations are modeled within each mode by Simulink function, which will be explored in detail in the next section, and an optimization based torque split strategy will also be presented in chapter 5.

The control strategy interprets the driver pedal intention as a torque request, which is a function of the maximum torque available at the current speed. If driver torque request is less than zero, then the vehicle is braking, the motor captures the maximum possible regenerative braking energy available within the inverter and battery constraints as well as vehicle operation mode.

4.4.1 Mode Selection

The criteria used in Simulink is to select the proper hybrid operation mode for all conceivable situations that may be encountered, fault modes were developed that can be used in the case of limited functionality of any or all powertrains. Four modes were developed in the stateflow environment with Simulink, the logic determines the criteria for transitioning between mode, which is shown in figure 20. First, the vehicle will go to default mode which is blended CD mode with high initial SOC when vehicle is enabled and ready, some diagnostic signals from fault detection block are highest priority checks, since vehicle will be forced into fault mode, like engine only mode when those diagnostics signals are active. Second, CS mode will start when high voltage battery SOC < CS_SOC_MIN which is minimum SOC threshold (18%) or CS switch on is triggered by the driver. Engine only mode will be entered only if normal vehicle operational modes are offline which means critical faults occur in the electric powertrain system. In sports mode, this mode can be triggered by the driver’s switch, and improve performance of vehicle.

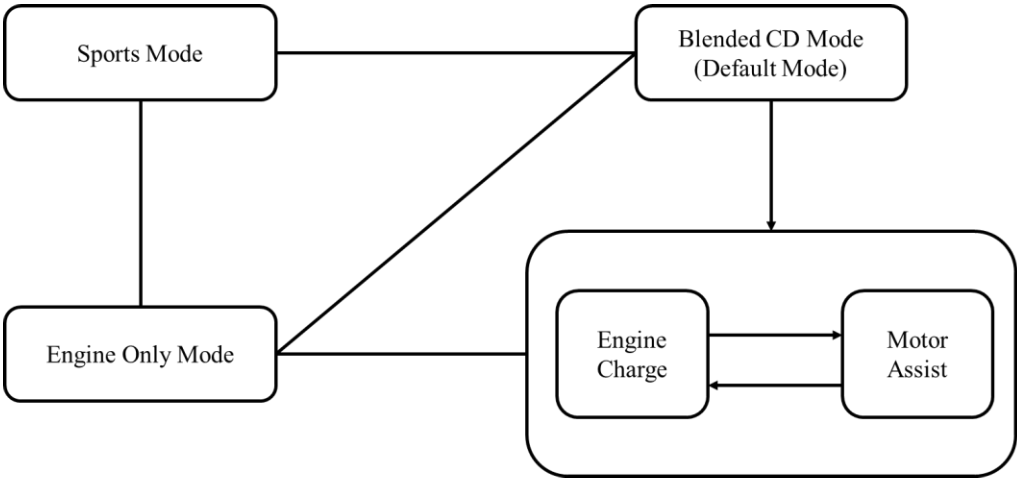


Figure 20 Mode selection in torque distribution

4.4.2 Blended Charge Depleting Strategy

A deterministic rule-based control strategy is developed to perform torque distribution between engine and electric mode within blended CD mode, to meet the torque requirements at the wheels, since there was no clutch between engine and electric motor, the engine output shaft will be always coupled to the motor, therefore, a motor dominant blended CD control strategy was developed to split the torque to meet the driver requested torque. Figure 21 provides an illustration of energy flows for blended CD mode. During the blended CD mode, the engine will be always on and produce torque at the wheels, so the entire driver torque request can be delivered by both engine and motor torque. However, since due to the limitation of our current clutch-less pre-transmission parallel architecture, the engine needs to be always on otherwise the engine will be a load to motor if vehicle is running in normal EV mode.

Driver requested torque can be calculated based on accelerator pedal position and brake pedal position and then converted to driver intended axle torque, the equation can be performed in the following:

$$T_{Axle}^{req} = \left(T_{eng}^{\max} + T_{mot}^{\max}\right) \cdot gear_{ratio} \cdot diff_{ratio}$$

The driver intended axle torque will be fed into mode selection block to perform torque split between engine and motor.

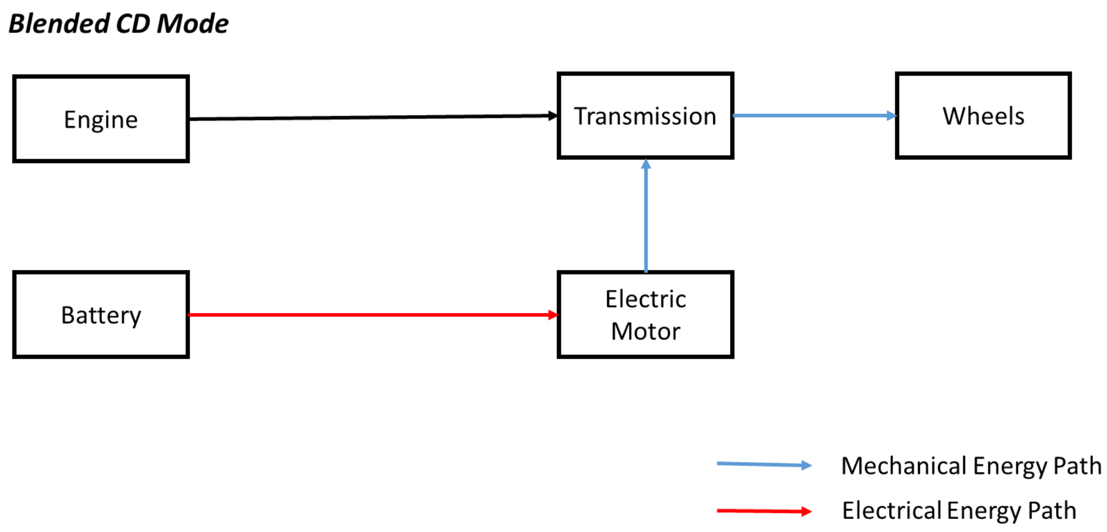


Figure 21 Energy flows in Blended CD mode

4.4.2.1 Torque Distribution Strategy

There are several control strategies employed during blended CD mode, such as engine-dominant blended strategy and electric-dominant blended strategy [28]. As mentioned previously, since there was no clutch between engine and motor, to analyze the impact of different control strategies on energy consumption. An engine -dominant is more likely to be implemented in our architecture. However, for the sake of optimizing the energy consumption in E&EC event, which is the longest and most resource intensive driving event in the competition [29]. Therefore, a new blended strategy was presented in this section:

Mode	Torque Request Threshold	Torque Distribution Strategy
Blended CD Mode	$T_{req} < T_{eng,\text{small}} + T_{mot,\max}$	$\begin{cases} T_{eng,cmd} = T_{small} \\ T_{mot,cmd} = \max\left(0, T_{req} - T_{small}\right) \end{cases}$
	$T_{req} > T_{eng,\text{small}} + T_{mot,\max}$	$\begin{cases} T_{eng,cmd} = \min\left(T_{eng,\text{opt}}, \left(T_{req} - T_{mot,\max}\right)\right) \\ T_{mot,cmd} = T_{mot,\max} \end{cases}$

Table 6 Torque request equations for Blended CD mode control strategy

Table 6 shows that torque distribution strategies involve two different sub-modes of operation associated with driver requested torque, and control strategies are discussed in detail in above table. when driver requested torque is less than the addition of maximum torque of electric motor and limited engine torque, the electric motor will produce majority of torque, while engine still needs to produce a small amount of torque, due to our clutch-less P2 architecture, this small amount of torque is discussed in later section. When driver requested torque is very large and requires power that is greater than maximum motor power, the electric motor will produce maximum power under high voltage battery limited power and inverter limited power, while the engine compensates the gap between motor command torque and driver requested torque but the torque commanded by engine is limited under optimal engine operating line.

In order to determine how much torque that engine can produce during CD mode for the sake of reducing UF-weighted total energy consumption, a set pf pre-defined engine operating line are determined to evaluate how much total energy are consumed during the E&EC event. Figure 22 shows various engine operating lines are defined according to the amount of percentage of max engine torque at current engine speed available. The optimal engine operating line was scaled down to different levels, as listed in table 7. The engine available torque based on current engine speed is limited by those lines.

Scale Factor	20%	30%	40%	50%	60%	80%	100%

Table 7 Scale factor for engine operating line

Figure 23 shows that with different scale factors, battery SOC depletes at different speed due to engine producing torque. It shows that the speed of SOC depleting increases when the scale factor decreases, which means that the contribution of engine also decreases.

Table 8 presents the UF-weighted energy consumption for different engine torque level. One can see that vehicle has the lowest fuel consumption which is only 4.07 gallon when the scale factor is 0.6. however, the UF-weighted energy consumption increases when the scale factor increases, in order to find a tradeoff between energy consumption and CD range, 0.3 of scale factor is selected to limit the engine torque during CD mode.

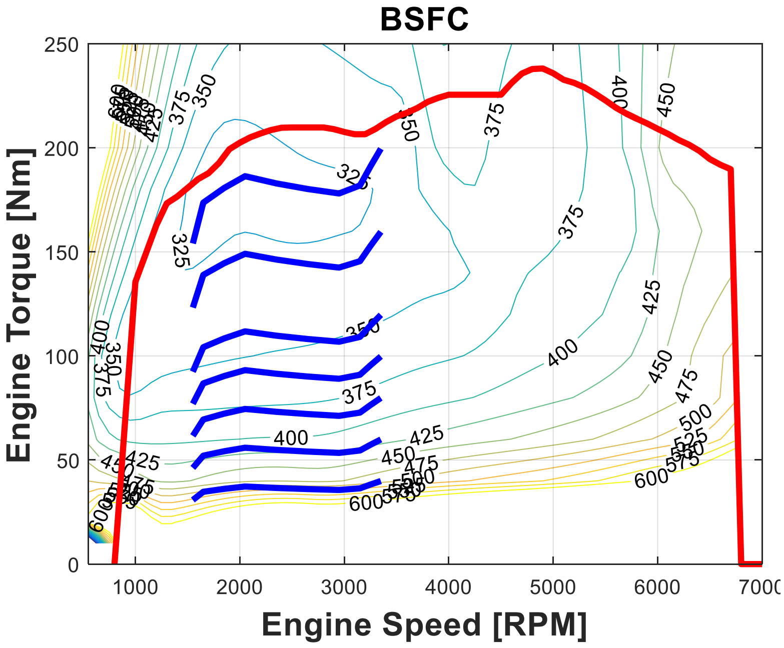


Figure 22 Various engine operating lines

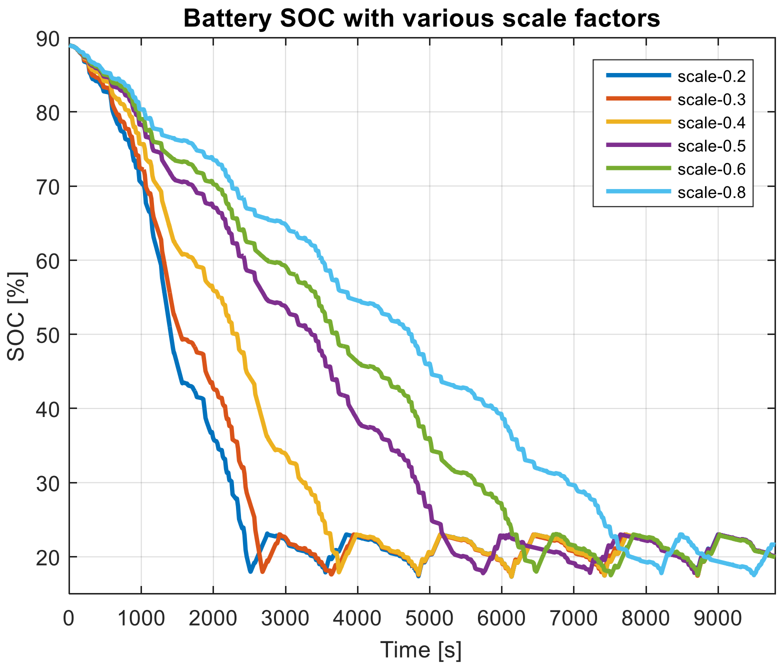


Figure 23 Battery SOC with various scale factors

Scaling factor	UF	CD Range (mile)	Fuel Consumption (Gal)	Vehicle Energy Consumption (Wh/km)			PEU WTW (Wh PE/km)
				CD Energy Consumption (Wh/km)	Equivalent CS Fuel Consumption (Wh/km)	UF-Weighted Energy Consumption (Wh/km)	
0.2	0.4425	23.32	4.1748	486.43	689.84	599.82	143.65
0.3	0.4813	26.39	4.1773	506.65	691.16	602.36	145.18
0.4	0.5858	36.36	4.1491	561.26	685.27	612.63	150.30
0.5	0.7406	59.43	4.1015	590.29	700.33	618.84	156.14
0.6	0.7750	67.28	4.0747	611.97	675.99	626.37	159.41
0.8	0.8366	86.79	4.0963	625.47	690.60	636.11	165.95
1	0.8703	102.92	4.1644	646.29			

Table 8 Vehicle Energy Consumption with different scale factors

4.4.2.2 Simulation Setup

To perform the blended control strategy analysis for PHEV, the E&EC city and highway drive cycle was chosen to run the simulation with initial 89% of SOC. The following section shows the results obtained in SIL for blended CD mode during a specified drive cycle as mentioned previously. Figure 24 shows the drive cycle in detail with average speed of 39 mph, and maximum speed of 55.3 mph, and Figure 25 shows the change of battery SOC, it's clear that engine torque is limited to certain level when the it's in CD mode so that vehicle has longer CD range.

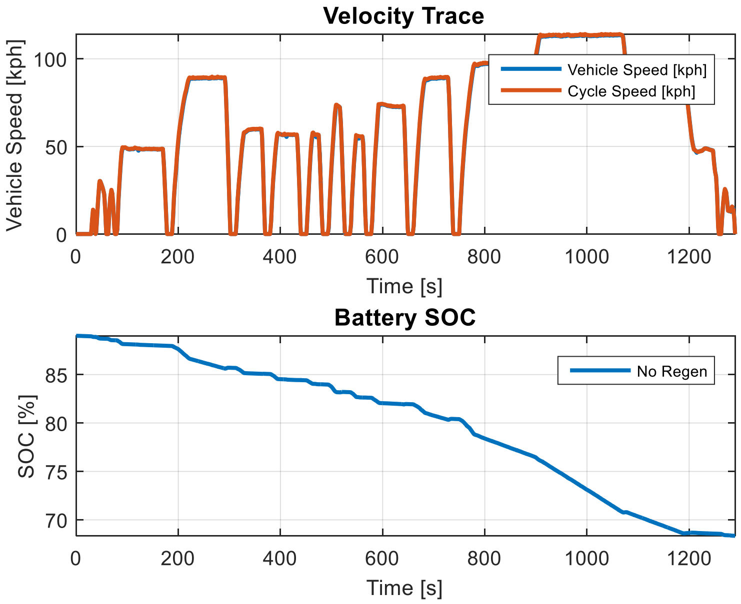


Figure 24 Speed trace and battery SOC

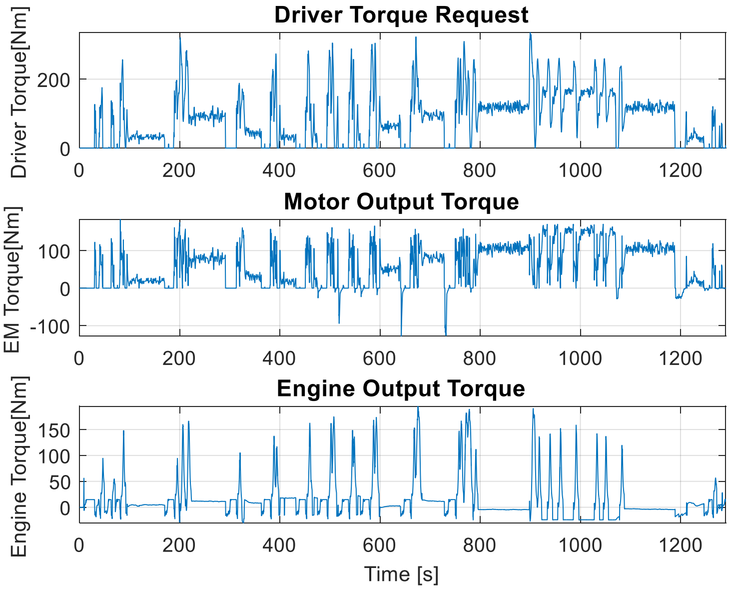


Figure 25 Driver Torque Request, Motor torque and Engine torque

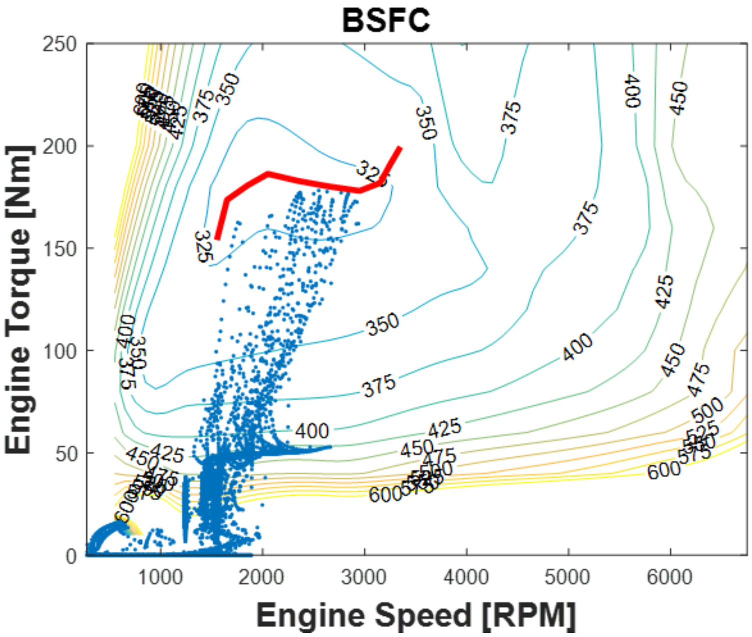


Figure 26 E&EC Drive Cycle Engine operation

4.4.3 Charge Sustaining Strategy

When SOC drops below a limit SOC, the vehicle mode will go to charge sustaining mode, in which the SOC of the battery sustains a certain level. In CS mode, both engine and electric motor are working together to produce torque at wheels. As expected, engine efficiency plays an important role in energy analysis, therefore, the key to improve the overall energy consumption is to let the engine work at the highest efficient operation. For CS control strategy, it’s undesirable to have significant energy coming from engine charging to the battery, since the path of energy from engine to the battery and then to the wheels is less efficient than the path of energy from engine directly to the wheels, as shown in figure 27. Therefore, it’s desirable to have engine working at optimal operation, and vehicle takes excess charging energy. The CS control strategy also involves three sub-modes of operation regarding to battery SOC and driver power demand. The control strategy is discussed in detail in the next section.

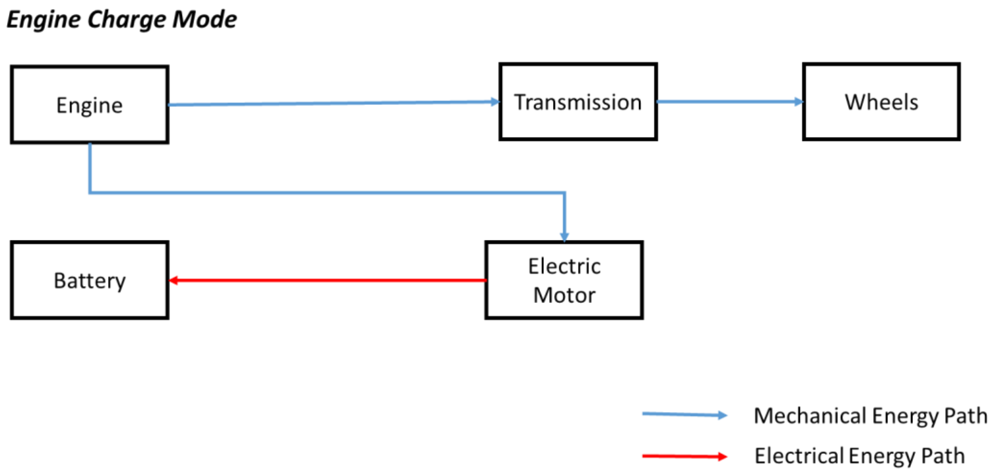


Figure 27 Engine Charge mode in CS mode

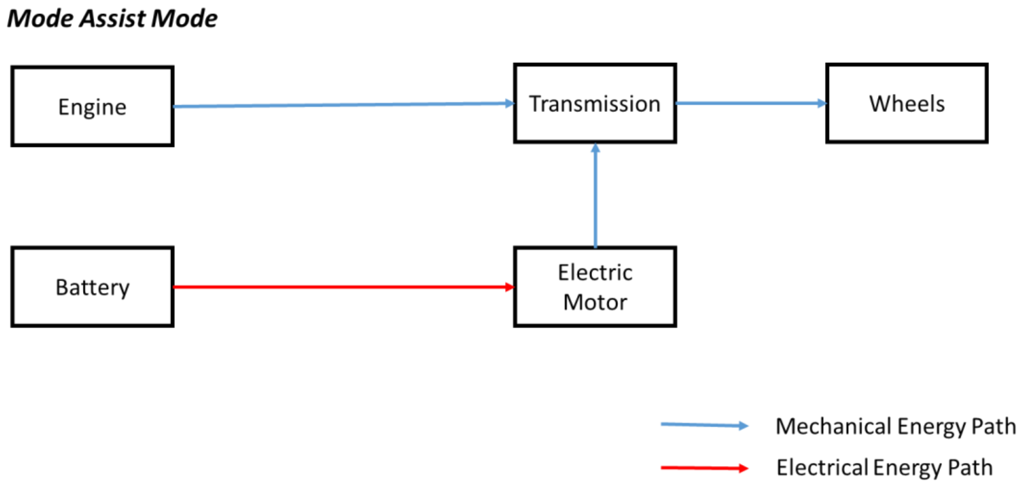


Figure 28 Motor Assist mode in CS mode

4.4.3.1 Torque Distribution Strategy

As discussed previously, the control strategy that often charges the high voltage battery by using the engine is expected to have greater fuel consumption in CS mode. Therefore, a new engine dominant control strategy in CS mode is discussed below.

1) When SOC drops below CS_SOC_MIN which is lower limit for battery SOC, and driver requested torque is less than optimal engine operation, then it’s desirable to have engine working at optimal operation, and excess energy is taken to charge the battery to increase the SOC, since motor assisting in this case will improve the engine operation region thus increasing the engine efficiency.

2) When SOC is higher than the pre-defined CS maximum SOC threshold, in addition, driver requested torque is pre-defined torque threshold, which means it's not mandatory to charge the battery to sustain the SOC, therefore, vehicle can be driven in normal CD blended mode, since as mentioned previously, the electric motor will produce majority of torque, while engine still needs to produce a small amount of torque. When driver requested torque is very large and requires power that is greater than maximum motor power, the electric motor will produce maximum power under high voltage battery limited power and inverter limited power, while the engine compensates the gap between motor command torque and driver requested torque but the torque commanded by engine is limited under optimal engine operating line.
3) When SOC drops below a critical SOC level and driver torque request is greater than desired operation region, if engine still works at optimal operating point then it's hard for battery to sustain at desired SOC level, battery working at low SOC may cause higher battery internal resistance, so the torque distribution strategy implemented in this mode is to let engine deliver maximum torque under current engine speed and motor acts as generator to charge the battery to increase the SOC. Table 9 below shows the detailed torque distribution strategies in CS mode. Figure 29 shows the sub-modes in charge sustaining mode and transition between two sub-modes.

Mode	Torque Request and SOC Threshold	Torque Distribution Strategy
CS Mode-Engine Charging	$\begin{cases} SOC < \text{CS\_SOC\_MIN} \\ T_{eng,opt} > T_{req} \end{cases}$	$\begin{cases} T_{eng,cmd} = T_{eng,opt} \\ T_{mot,cmd} = \max\left(-\mathrm{T}_{mot,\max}, T_{req} - T_{eng,opt}\right) \end{cases}$
	$\begin{cases} SOC < SOC\text{\_critical} \\ T_{eng,opt} \le T_{req} \end{cases}$	$\begin{cases} T_{eng,cmd} = T_{eng,\max} \\ T_{mot,cmd} = \max\left(-T_{mot,\max}, \min\left(T_{\mathrm{mot,max}}, \left(T_{req} - T_{\mathrm{eng,max}}\right)\right)\right) \end{cases}$
CS-Mode-Motor Assisting	$\begin{cases} SOC \ge \text{CS\_SOC\_MAX} \\ T_{req} < T_{eng,\mathrm{small}} + T_{mot,\max} \end{cases}$	$\begin{cases} T_{eng,cmd} = T_{small} \\ T_{mot,cmd} = \max\left(0, T_{req} - T_{small}\right) \end{cases}$
	$\begin{cases} SOC \ge \text{CS\_SOC\_MAX} \\ T_{req} > T_{eng,\mathrm{small}} + T_{mot,\max} \end{cases}$	$\begin{cases} T_{eng,cmd} = \min\left(T_{eng,\mathrm{opt}}, \left(T_{req} - T_{mot,\max}\right)\right) \\ T_{mot,cmd} = T_{mot,\max} \end{cases}$

Table 9 Torque Control strategy in CS mode

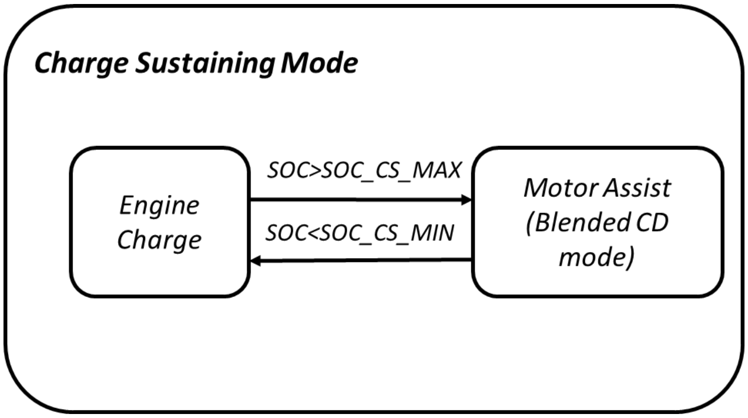


Figure 29 Charge Sustaining Mode

4.4.3.2 Simulation Setup

As discussed previously, CS control strategies involve three cases associated with current battery SOC and driver power demand. The E&EC city and highway drive cycle is used. As shown in Figure 30. the difference between initial SOC and final SOC is within allowable limit, which is 5% for HEV.

Figure 32 the engine operating points for E&EC drive cycle. It's clear that most of engine operating points are located under optimal operating line which is the highest efficiency for engine.

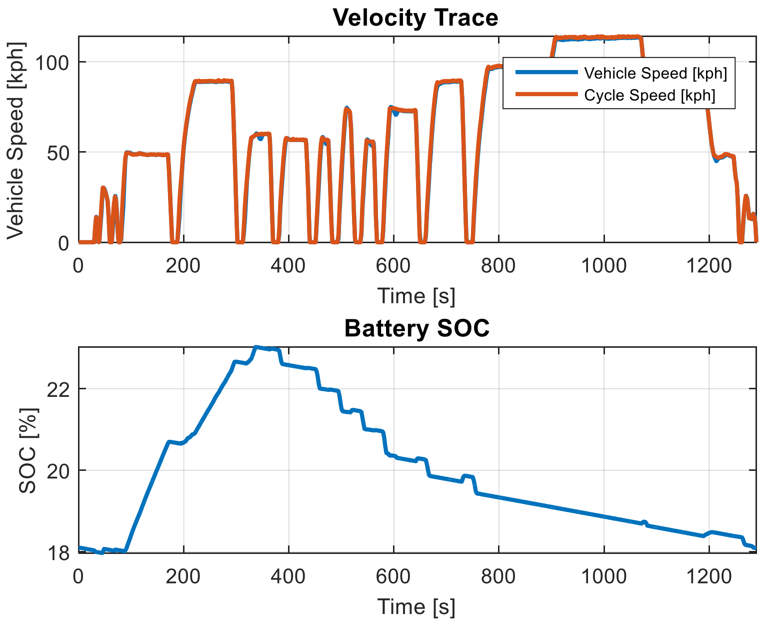


Figure 30 Speed Trace and SOC under CS mode

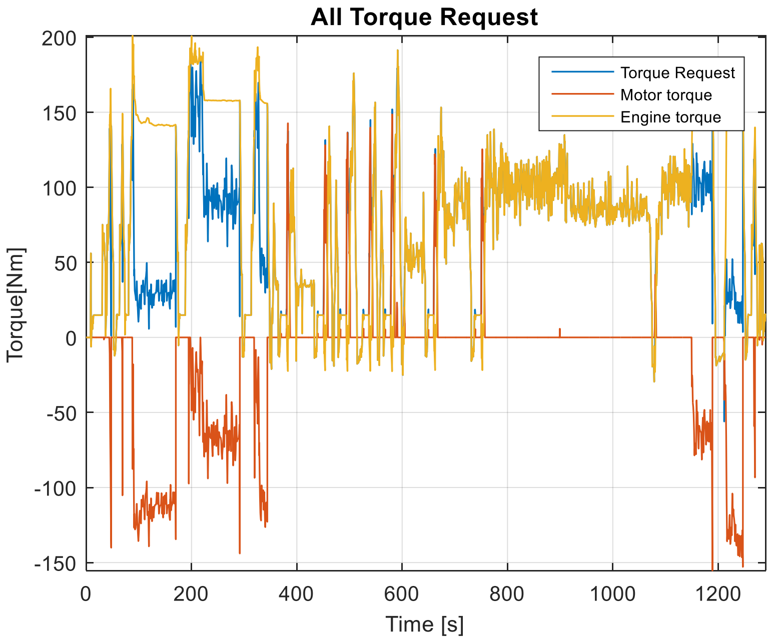


Figure 31 All torque request for City and Highway drive cycle

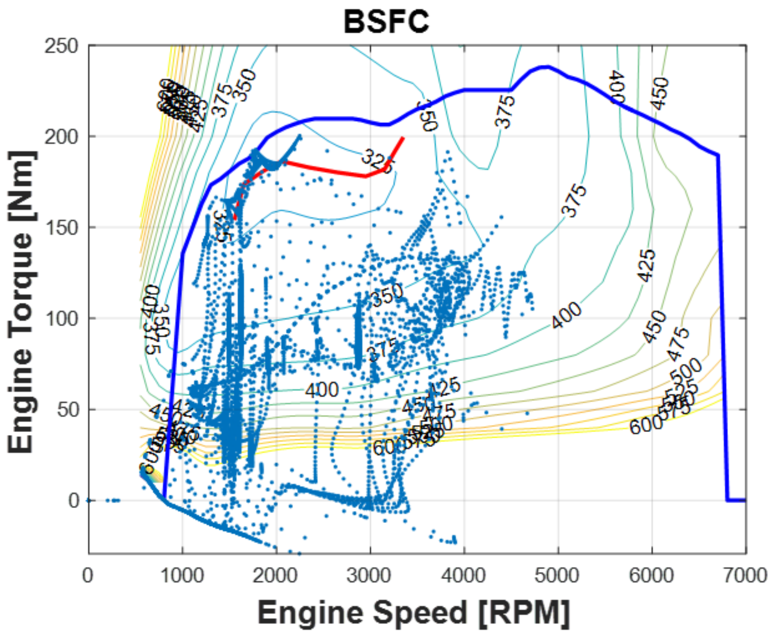


Figure 32 Engine Operating Points under CS mode

4.4.4 Regenerative Braking Mode

In hybrid electric or pure electric vehicles, the regenerative braking can effectively improve the fuel economy by recuperating the kinetic energy during the deceleration. The regenerative braking can be coupled with mechanical brake to decelerate the vehicle at the same time. Figure 33 illustrates the energy flow from wheels to the battery. Figure 34 shows the drive cycle with 60mph to 0mph braking and battery SOC changes with regenerative braking enabled and disabled. It’s clear that battery SOC increases approximately by 0.2% when vehicle decelerates and the energy was captured back to the battery.

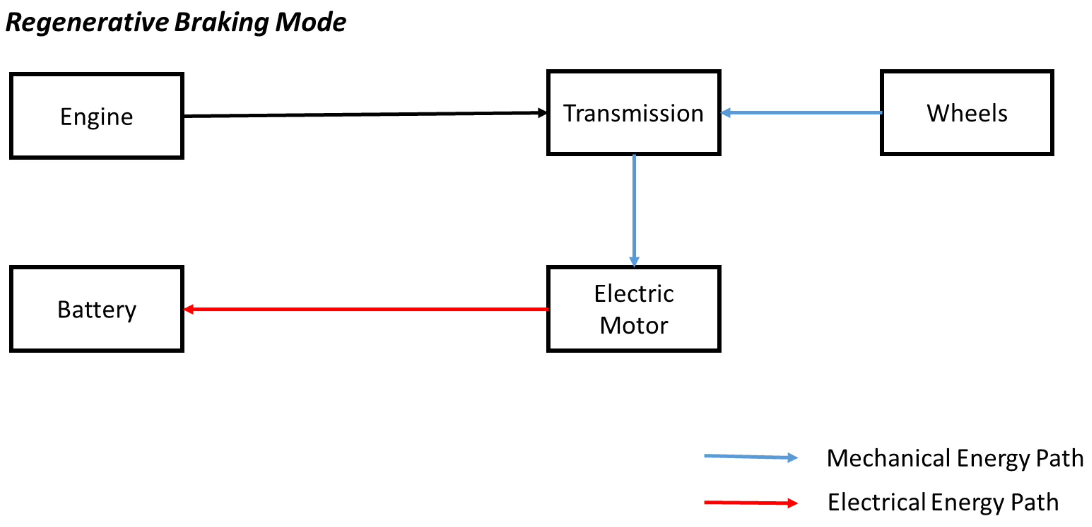


Figure 33 Energy path for Regenerative Braking

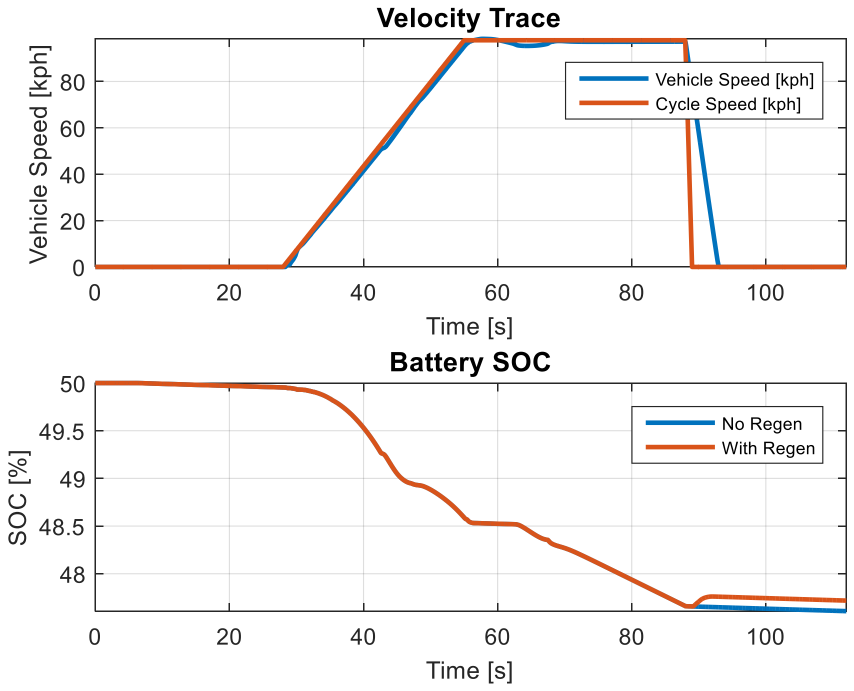


Figure 34 Speed Trace and Battery SOC with/without Regen

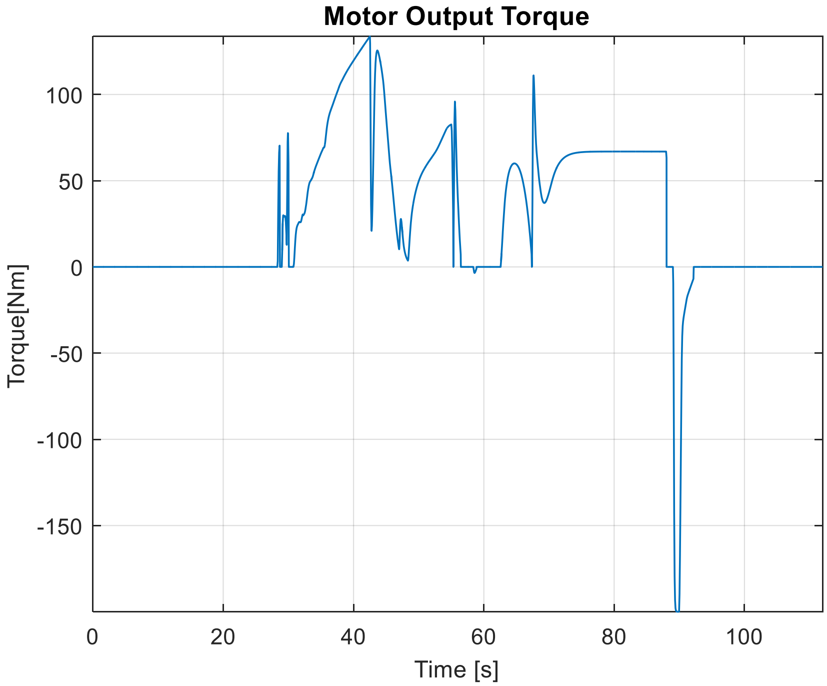


Figure 35 Motor output torque

4.5 Torque Request Subsystem

During the transient conditions, the engine cannot follow the driver torque request so this can be solved by motor compensation, since the engine is much slower than the electric motor. Figure 36 below shows the relationship between engine torque and electric motor torque.

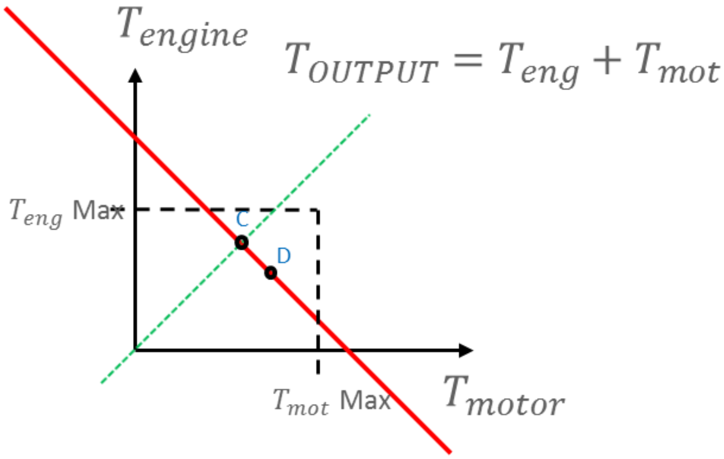


Figure 36 Engine and motor torque control

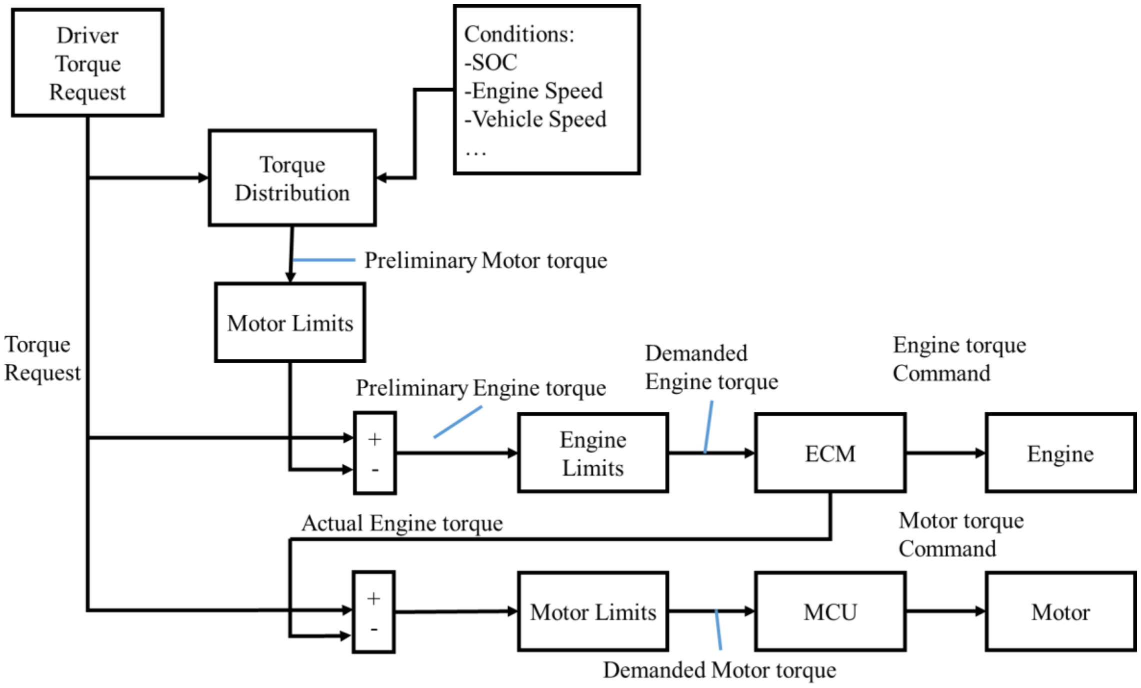


Figure 37 Engine and electric motor torque request

If driver torque request changes from point C to point D in figure 36, due to the limit of engine response dynamics, the engine cannot change operating points from C to D instantaneously, therefore, during transient condition, the difference between actual engine torque and driver torque request is sent to the electric motor, so that the motor can compensate the torque difference faster than the engine. Although this strategy has small impact on fuel consumption, the drivability is greatly improved by this method.

4.6 Energy Analysis

As mentioned previously, Emissions and Energy Consumption (E&EC) in EcoCAR3 is an important event during the competition where the on -road testing is conducted over a pre- defined drive cycle to evaluate the total energy consumption of the vehicle that each team designed. In this section, a E&EC full drive cycle was used with over approximately 103 miles, which consists of drive to track, seven repeating City/Highway around circle track and drive back from track drive cycle, as shown below. This section outlines the energy analysis over EcoCAR3 E&EC drive cycle based on the control strategies discussed in previous sections.

- To Track*1
- CityHighway*3
- 20 minutes’ break
- CityHighway*4
- From Track*1

	E&EC Drive Cycle
Maximum Speed (mph)	70
Average Speed (mph)	37.9
Overall Distance (mile)	102.7
Maximum Grade (%)	-12.27

Table 10 E&EC drive cycle profile

4.6.1 Performance for E&EC Drive Cycle

In this section, simulation was conducted based on E&EC full drive cycle, the vehicle was driven in CD and CS mode to test the control strategies discussed in previous sections. As shown in figure 38, the vehicle drives around 25 miles when battery SOC is lower than CS transition threshold, and battery SOC sustains at stable level when vehicle is in CS mode.

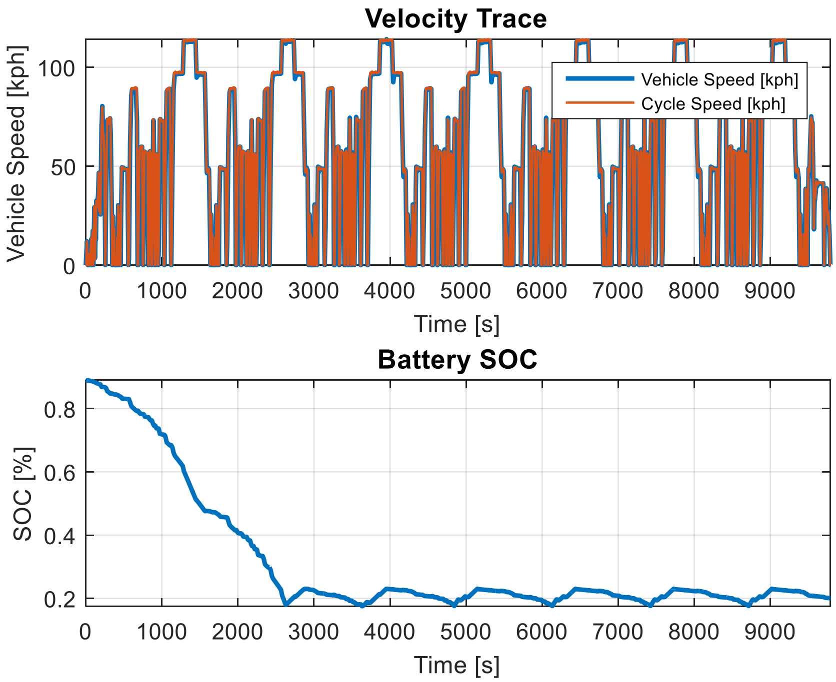


Figure 38 E&EC Full drive cycle and battery SOC depletes

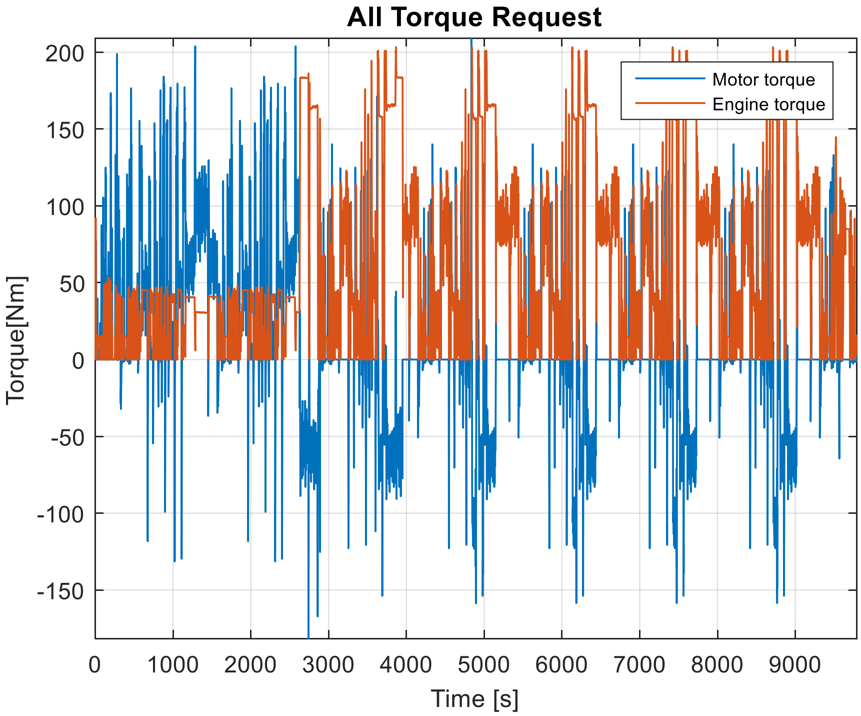


Figure 39 Motor torque and engine torque request

With engine working during CD mode, the CD range of vehicle was significantly extended, however, the energy consumption increases due to fuel consumption in CD mode. Figure 39 shows the all torque request during the entire drive cycle, one can see that motor delivers most torque request in CD mode and also captures the kinetic energy during regenerative braking. In CS mode, energy operates at optimal operating line and extra torque is used to charge the battery to sustain SOC level.

4.6.2 Energy Consumption

To evaluate the energy consumption for CD and CS control strategies in E&EC drive cycle, For UF-weighted energy consumption, fuel and electric consumption needs to be calculated by applying UF to the CD and CS modes, the equations below show the total energy consumption calculation [29]:

$$Energy\ Consumption_{UF-weighted}[kWh/km] = (EC_{CD} * UF + EC_{CS} * (1 - UF))[kWh/km]$$

Table 11 shows the vehicle energy consumption for entire drive cycle, which meets the team’s VTS requirements.

Table 11 Vehicle Energy Consumption for E&EC drive cycle

UF	CD Range (mile)	Fuel Consumption (Gal)	Vehicle Energy Consumption (Wh/km)			PEU WTW (Wh PE/km)	GHG WTW (g GHG/km)
			CD Energy Consumption (Wh/km)	Equivalent CS Fuel Consumption (Wh/km)	UF-Weighted Energy Consumption (Wh/km)		
0.4884	26.98	4.50	506.06	724.91	618.03	154.08	175.86

5 Optimization-based Energy Management Strategy

5.1 Introduction

As discussed in the previous section, energy management strategy are algorithms that distribute the power between engine and electric motor to reduce the energy consumption and improve the performance of HEVs, energy management takes vehicle states, like pedal positions, battery SOC, etc. to make decisions.

A modified equivalent consumption minimization strategy (ECMS) is proposed in this section, the ECMS is a real-time optimization method, which calculates the instantaneous fuel consumption at each time step in the drive cycle and offers locally optimal operating point of engine and electric motor [15]. The ECMS is designed by calculating the total energy consumption which is the sum of actual fuel consumption of engine and virtual electric energy consumption of electric motor. Typically, this strategy is calculated based on real-time and no predictions are necessary but only few vehicle state constraints are needed, such as battery SOC, driver torque request at the wheels, etc. Compared to deterministic rule-based control strategy which is discussed in the previous sections, this strategy can offer optimal torque distribution between ICE and EM to improve the fuel economy while maintaining battery SOC at the same level.

In this chapter, the instantaneous equivalent fuel consumption is analyzed in charge sustaining mode, and then torque distribution strategy based on ECMS is proposed to find the torque optimization among driver torque request at each time step, and finally a penalty function for state constraints and charge sustainability is developed to guarantee that the battery SOC does not exceed the limit.

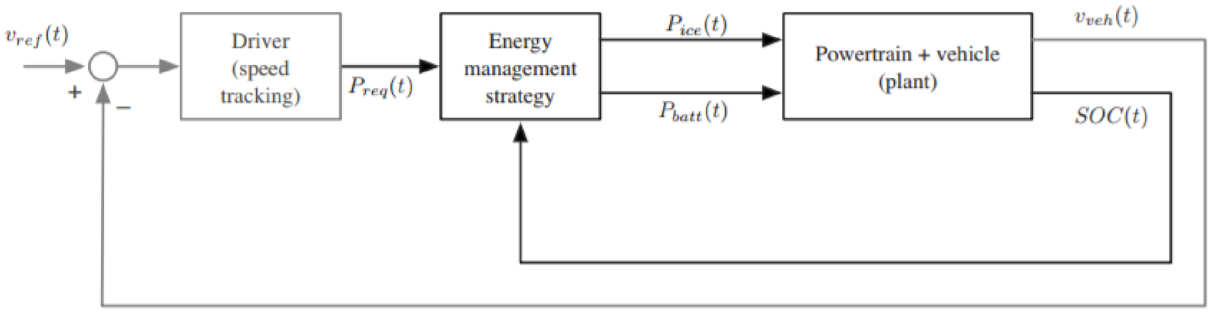


Figure 40 Energy Management Strategy in HEVs

5.2 Instantaneous Equivalent Fuel Consumption Analysis

In this section, an equivalent consumption minimization strategy (ECMS) is implemented in P2 parallel PHEV, the main objective of this control strategy is to find the optimal torque distribution between the engine and the electric motor. Figure X shows that this optimization-based control strategy flow chart. The ECMS requires the information from driver torque request, and current vehicle status, such as engine speed, battery state of charge (SOC), motor speed to calculate near optimal torque split, and then battery SOC is fed into parameter correction block to correct equivalent factor s(t), which represents the cost to the electrical energy consumption.

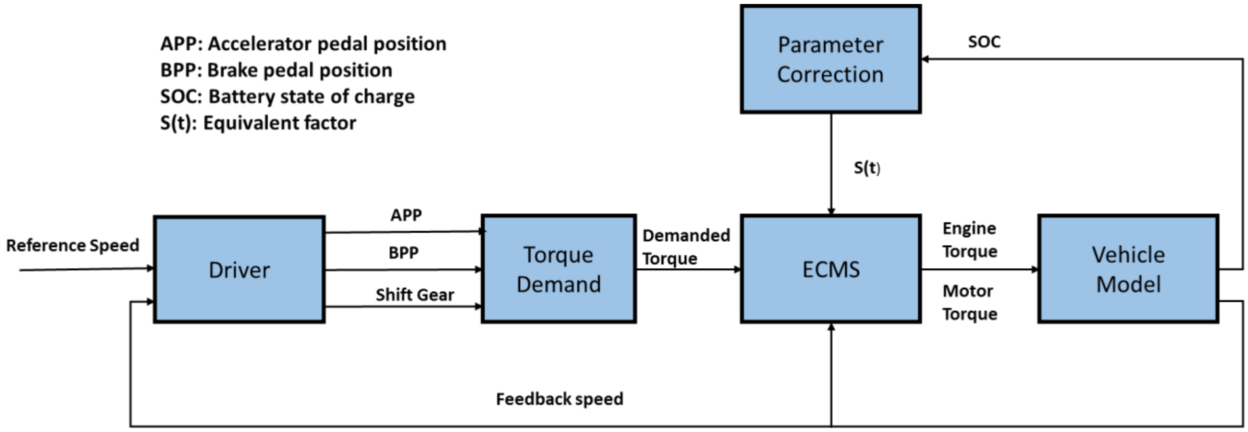


Figure 41 ECMS torque control strategy flow chart

This real-time control strategy contains three aspects: instantaneous equivalent fuel consumption equation, SOC correction and instantaneous optimization.

Instantaneous equivalent fuel consumption is the concept that battery can be seen as energy buffer [15], and during charge sustaining mode for PHEV, the electrical energy consumed needs to be replenished using fuel from the engine charging in the future, therefore, an equivalent energy consumption function associated with virtual electric energy consumption is analyzed and built to be objective function, which is discussed in the following.

$$J_{eq} = \dot{m}_{ice}(t) + s(t) \cdot \dot{m}_{batt}(t)$$

In the equation, $\dot{m}_{ice}(t)$ means instantaneous engine fuel consumption (g/s), it can be calculated by looking up in the map which is the function of engine torque and engine speed, as shown in figure 42 $\dot{m}_{batt}(t)$ means the equivalent future fuel consumption which can be added to the actual engine fuel consumption to represent the instantaneous fuel consumption in charge sustaining mode. $s(t)$ is equivalent factor which assigns a cost to the use of electric energy, converting electrical energy into equivalent fuel energy. In this control strategy, when battery SOC is higher than target SOC, the equivalent factor can be assigned to a smaller value, then the cost of electrical energy becomes lower and battery tends to be discharged like charge depleting mode, when the SOC is lower than target SOC, the equivalent factor can be assigned to a bigger value which increases the cost of using electrical energy, the battery tends to be charged like charge increasing mode, therefore, this value plays an important role in regulating battery SOC, which is discussed in the next section.

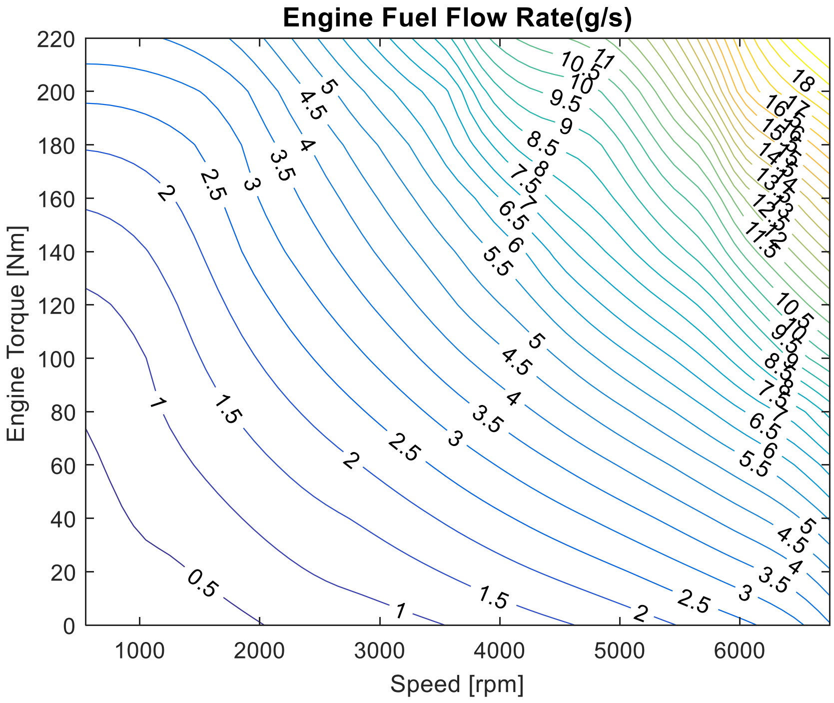


Figure 42 Engine Fuel Flow Rate Map

In the discharge case, the battery and engine can provide power to the wheels at the same time, however, in order to replenish the energy consumed in this discharge phase, the electrical power needs to be charged using fuel from engine charging in the future. Figure 43 shows the energy path in the discharge phase. The instantaneous fuel consumption equation in discharge case can be shown in the following:

$$J_{eq} = \dot{m}_{ice}\left(t\right) + s\left(t\right) \cdot \frac{T_m \cdot \omega_m}{\eta_{dis}\eta_{mot}Q_{lhv}}$$

Where T_m is motor command torque (Nm), ω_m is motor speed (rpm), η_{dis} is battery discharge efficiency, η_{mot} is motor efficiency, Q_{lhv} is the fuel lower heating value (the energy content per unit of mass).

In this case, $s\left(t\right)$ can be represented as the chain efficiencies of transforming fuel energy into electrical energy, so $s\left(t\right) = 1/\eta_{eng}\eta_{chg}$. From the energy path below, one can see that the electrical energy consumed in discharge phase will be replenished in the future by engine, and thus in the energy domain, the chemical energy converts to the mechanical energy and then to the electrical energy, which suffer the energy losses in this process.

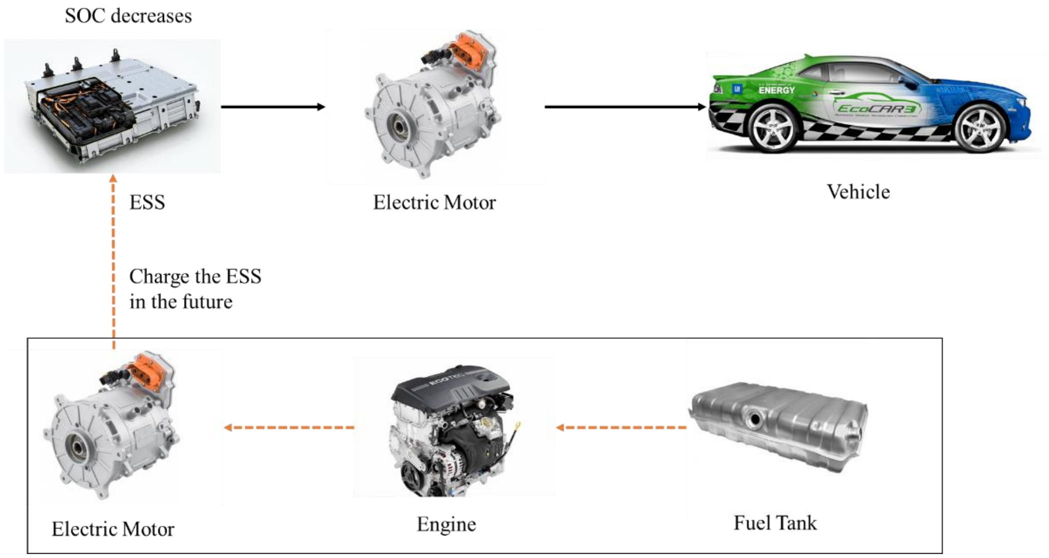


Figure 43 Energy path in discharge phase

In the charge case, the instantaneous fuel consumption equation in discharge case can be shown in the following:

$$J_{eq} = \dot{m}_{ice}(t) + s(t) \cdot \frac{T_m \cdot \omega_m}{Q_{lhv}} \eta_{mot} \eta_{chg}$$

Where η_{chg} is battery charge efficiency.

During the charge phase, the electrical power that charged by the engine in the future will save the actual fuel, the mechanical energy provided by the engine is converted into electrical energy, battery SOC increases, as shown in figure 44, the energy path in the rectangle represents that the electrical energy charged by engine will be depleted in the future to save the actual energy.

The equivalent factor shows the chain of efficiency of converting electrical power to fuel as well, which is the same with equivalent factor in discharge phase.

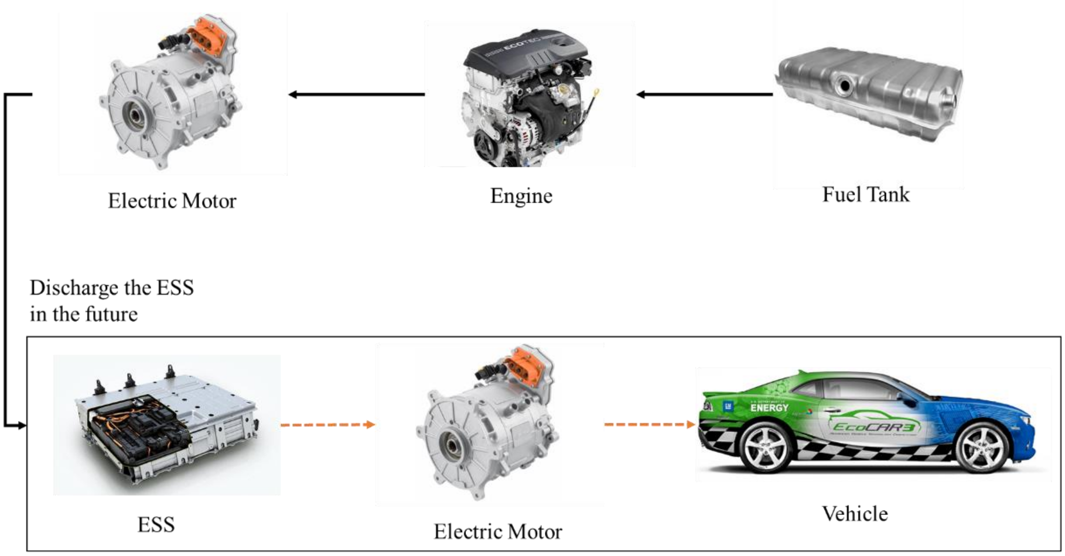


Figure 44 Energy path in charge case

5.3 Torque Distribution Strategy

As discussed in the previous section, the instantaneous fuel consumption has been presented to show the total fuel consumption including actual fuel consumption and virtual fuel consumption associated with electrical energy, the key point of ECMS is to find the instantaneous torque optimization which takes account for all efficiencies of converting fuel to electrical energy or vice versa.

The purpose of torque distribution optimization is to take driver request torque, vehicle speed, accelerator pedal position, equivalent factor, current gear position in the transmission and engine speed to find the optimal torque split between engine and electric motor.

In order to find the optimal torque split between engine and electric motor, the minimal instantaneous fuel consumption has to be found and then determine the respective engine torque and motor torque corresponding to the minimal total fuel consumption. In this section, the equivalent fuel consumption is calculated by using discretized electric motor torque as control variable, since the driver torque request is fixed at each time step, the motor torque that gives the lowest equivalent fuel consumption is selected. Figure 45 shows that at each time step, the sum of motor torque candidate and engine torque candidate is always equal to driver torque request, therefore, in this case, torque request can be divided to several control variables. Figure X shows the ECMS control algorithm flowchart which clearly explain how the optimal torque distribution is obtained in this control algorithm. The equation below shows the objective function:

$$J_{eq,\min} = \min\left[J_{eq}(k)\right]$$

Per the P2 parallel architecture, the torque and speed are limited by mechanical constraints

$$\omega_{\min} \le \omega \le \omega_{\max}$$

$$T_{\min}(\omega_m) \le T \le T_{\max}(\omega_m)$$

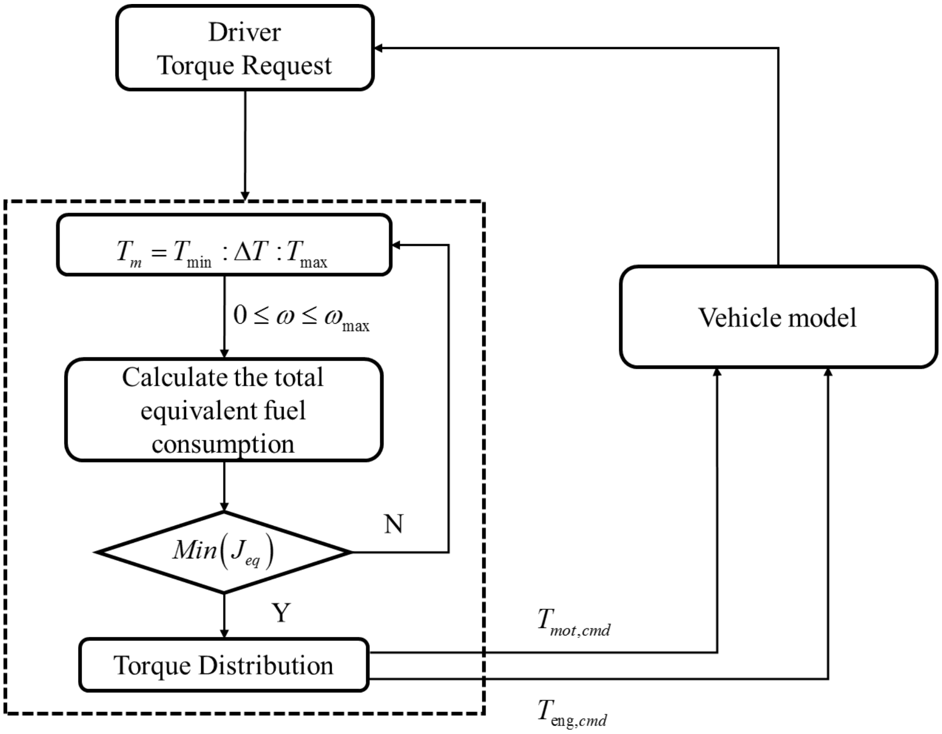


Figure 45 ECMS Control Algorithm

5.3.1 Motor torque candidate and engine torque candidate

As discussed previously, the motor torque and engine torque candidate can be calculated by driver torque request and their actuator mechanical constraints, as shown in figure 46. To calculate each possible motor torque pairs at each time step, the lower limit for motor torque is

$$T_{\text{mot,min}}(\omega_m) = \max\left(T_{req}(\omega_m) - T_{eng,\max}(\omega_m), T_{mot,\max,regen}(\omega_m)\right)$$

The maximum available motor regenerative torque is based on the motor limit and battery capability. The upper limit for motor torque candidate is

$$T_{\text{mot,max}}(\omega_m) = \min\left(T_{req}(\omega_m) - T_{\text{mot,avail}}(\omega_m)\right)$$

The upper and lower motor torque are used for determining available control variables at current motor speed. The motor torque candidate can be

$$T_{mot,candidate} = \left[T_{mot,\min} : \Delta T : T_{mot,\max}\right]$$

Therefore, the respective engine torque limit can be

$$T_{eng}\left(\omega_m\right) = T_{req}\left(\omega_m\right) - T_{mot,candidate}$$

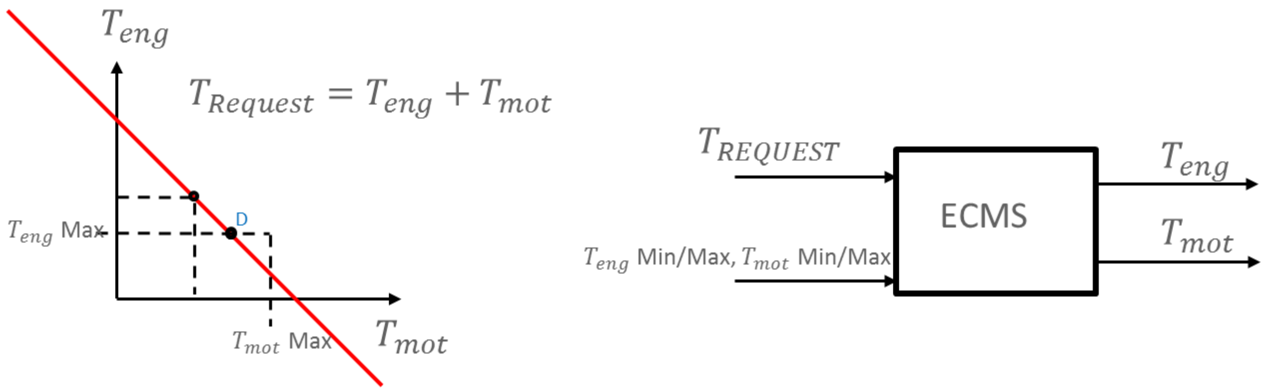


Figure 46 Torque control system and actuators constraints

5.3.2 Torque Split Optimization

After obtaining the motor torque candidate and engine torque candidate, the control algorithm in figure 45 is main process for optimizing torque split between engine and motor in real time. The ECMS algorithm takes discretized motor torque as control variables and calculate the total equivalent fuel consumption for each combinations of motor torque candidates and engine torque candidates, and then minimal equivalent fuel consumption is selected to find the most efficient engine torque request and motor torque request for driver total torque demand at each time step. Once the most efficient motor torque request is determined, it can be sent to the engine torque determination block to calculate engine torque request to the ECM.

5.3.3 Torque Request Subsystem

The engine torque request determined by HSC usually changes rapidly, therefore a rate limiter is necessary to prevent the engine from changing operating points too rapidly. A torque request strategy for engine and electric motor was proposed to improve the drivability, as shown figure 47.

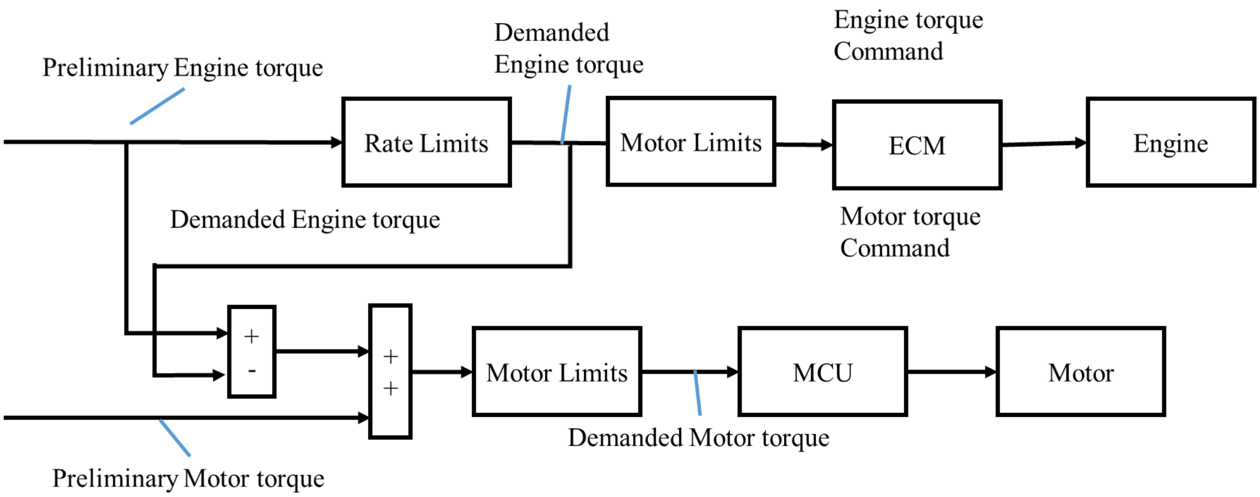


Figure 47 Engine torque and Motor torque request subsystem

The preliminary engine torque coming from torque distribution is limited by rate limit if the engine operating point change too fast, and the difference between preliminary engine torque and demanded engine torque is added to the preliminary motor torque to meet driver torque request.

5.4 SOC Correction

The ECMS algorithm does not guarantee the sustainability of battery state of charge, since it only finds the minimal total equivalent fuel consumption. In charge sustaining mode for HEVs, the difference between initial battery SOC and final SOC should be limited to 4%, therefore, a penalty function is applied to the objective function to change the cost of electrical energy, the penalty is shown below [15]:

$$p = 1 - \left(\left(SOC(t) - SOC_{target}\right) / \left(SOC_{\max} - SOC_{\min}\right) / 2\right)^3$$

This subsystem compares the current SOC to targeted SOC for charge sustaining mode, based on the results of comparison, this subsystem outputs an equivalent factor that is used for weighting the cost of electrical energy consumption in instantaneous equivalent fuel consumption, as shown in equation below:

$$J_{eq} = \dot{m}_{ice}(t) + p(t) \cdot s(t) \cdot \dot{m}_{batt}(t)$$

As shown in figure 48 below, when SOC is smaller than target SOC which is 18% in this case, the penalty factor is greater than 1, then higher cost is assigned to the electrical power, and battery tends to more likely be charged, when the cost is lower, the battery is more likely discharged.

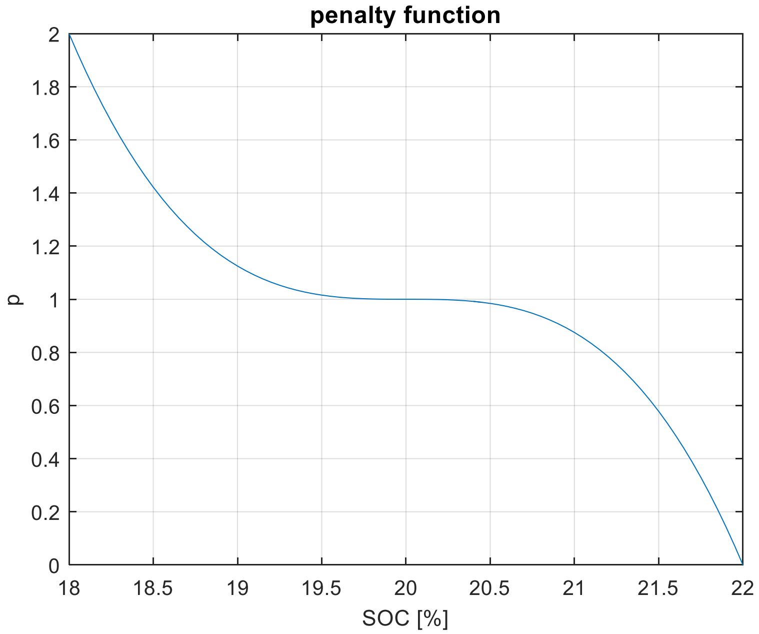


Figure 48 Penalty function for SOC correction

In order to show the SOC sustainability based on penalty function, the figure 48 shows that with the SOC correction function, the battery SOC can sustain at certain level, and only 0.48% of battery energy lost. Without this SOC correction function, the controller tends to use electrical energy more likely since the electrical energy has less contribution to the equivalent fuel consumption, that is, the path of energy from engine to the battery and then to the wheels is less efficient than the path of energy from engine directly to the wheels. Therefore, the adjustment of equivalent factor in real-time allows the vehicle to sustain battery SOC adaptively based on drive cycles. Figure 49 shows the battery SOC changes when SOC correction was applied for 505 drive cycle. It’s clear that battery SOC was back to the targeted SOC when SOC correction was applied.

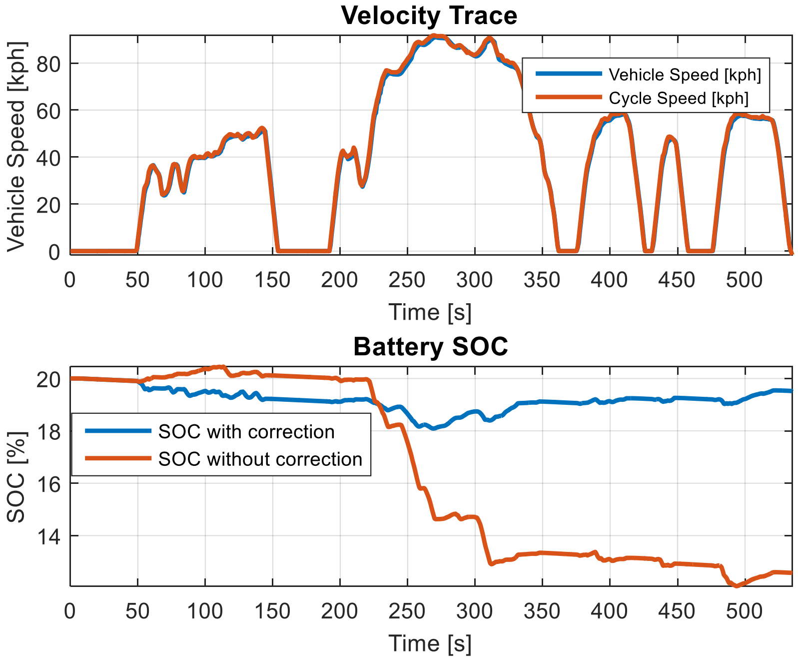


Figure 49 Vehicle Speed trace and battery SOC with or without correction

5.5 Simulation Results

According to the discussion above, the real-time optimization based control strategy was implemented in MATLAB/Simulink, as shown in Appendix. in this section, CS mode is performed in the simulation based on 505 drive cycle, figure 50 shows the speed trace and SOC profile in charge sustaining mode under new control strategy with SOC correction strategy, where the initial SOC and final SOC are almost identical, there is only 0.36% difference between them.

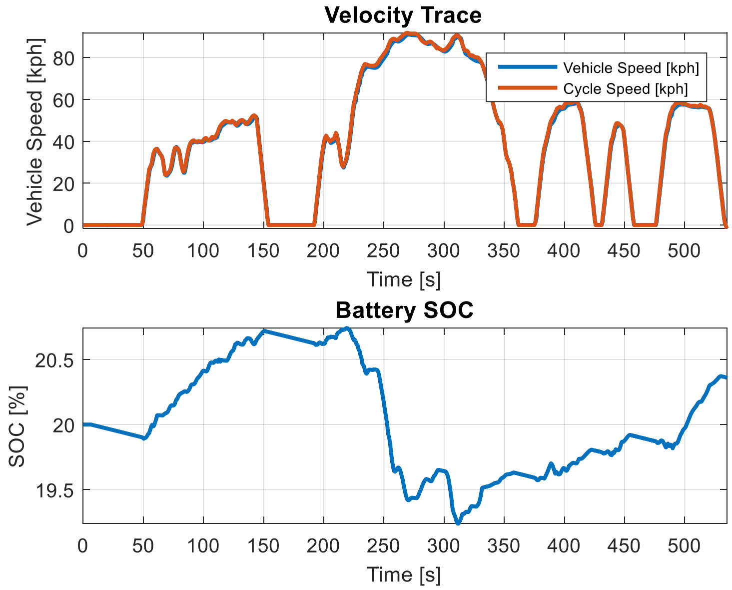


Figure 50 505 Speed Trace and Battery SOC in CS mode

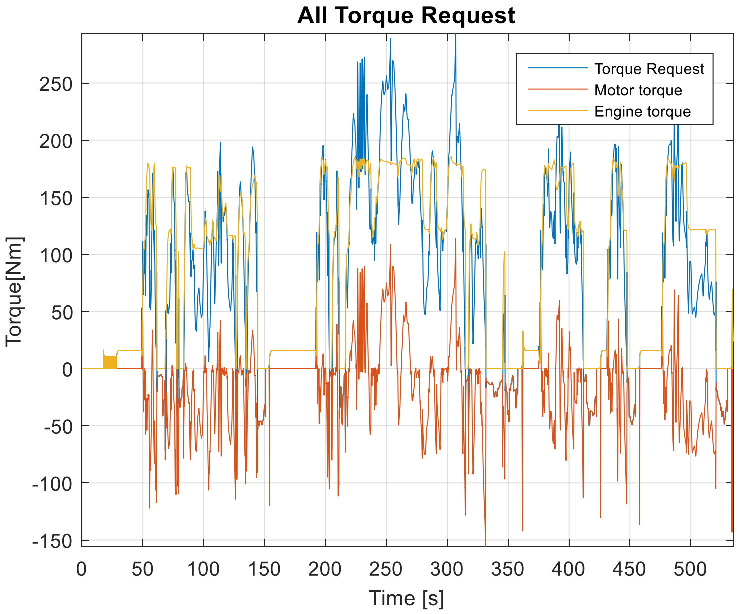


Figure 51 All torque requests using optimization based control strategy

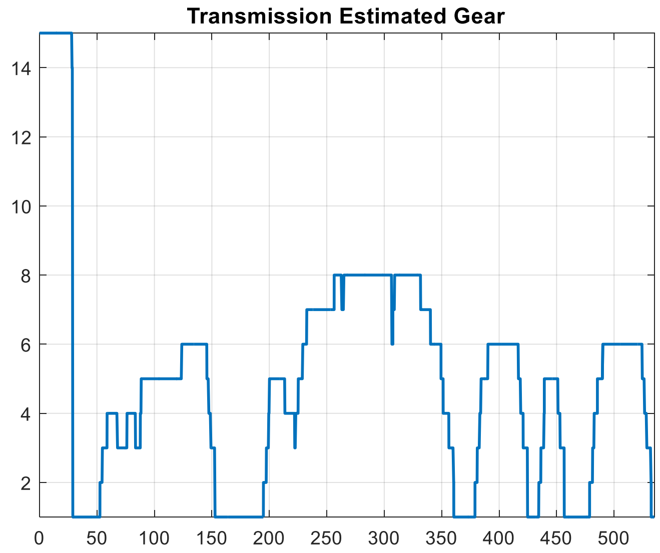


Figure 52 Transmission Estimated Gear

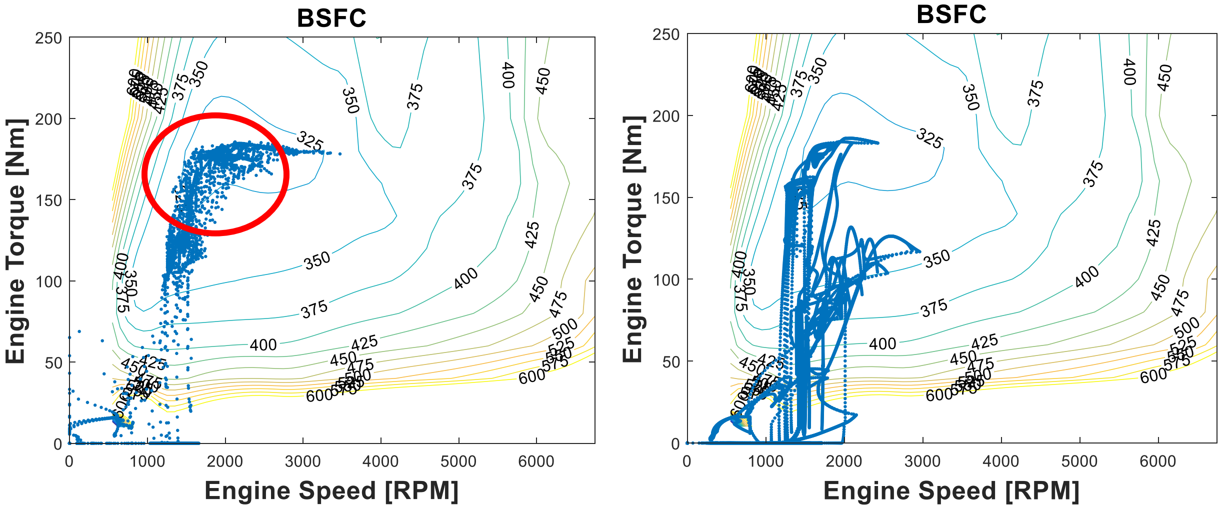


Figure 53 a) Engine Operating Points of 505 drive cycle for ECMS, b) Engine Operating Points for rule-based control strategy

Figure 53 above shows that engine operating points in 505 drive cycle for rule-based control strategy and ECMS controller, from the figure, one can see that most of engine operating points are in the lowest fuel consumption area under new control strategy, which is shown in the red circle.

5.6 Energy Consumption Comparison

A rule-based control strategy was discussed in chapter 4, which has four different modes, charge depleting mode is default mode, and when battery SOC is lower than a pre-defined threshold, the charge sustaining mode is triggered to sustain the SOC at stable level.

To compare the energy consumption between the optimization based control strategy and rule-based control strategy, four EcoCAR3 drive cycles are used in the MIL environment which include 505, HWFET and US06 city and highway portion. Figure 54, 55, 56, 57 show all four drive cycles trace and SOC profile with two different control strategies, and all engine operating points for optimization based controller plots are shown in Appendix. Table 12, 13, 14 15 show the SOC-corrected total energy consumption comparison between two control strategies during charging sustaining mode.

SOC -corrected fuel consumption can be calculated by the following equation [29]:

$$FC_{SOC-corrected}\left[\frac{kg}{km}\right] = \frac{\left(Mass_{fuel}[kg] + \frac{\frac{EC_{electric,CS}[kWh]}{0.25}}{LHV_{fuel}\left[\frac{kWh}{kg}\right]}\right)}{cycle\ distance[km]}$$

$$EC_{equivalent\ fuel,CS}\left[\frac{kWh}{km}\right] = FC_{SOC-corrected}\left[\frac{kg}{km}\right] * LHV_{fuel}\left[\frac{kWh}{kg}\right]$$

One can see that both two strategies can sustain SOC within pre-defined limit. However, ECMS strategy decreased the total energy consumption by 7.1%, 8.5% 5.7%, 1.6% compared with the rule-based control strategy, while maintaining small SOC difference during CS mode. Therefore, from energy consumption in table 12,13,14, 15, it's clearly that ECMS controller reduced more energy consumption during city drive cycles than highway drive cycles.

5.6.1 505 Drive Cycle

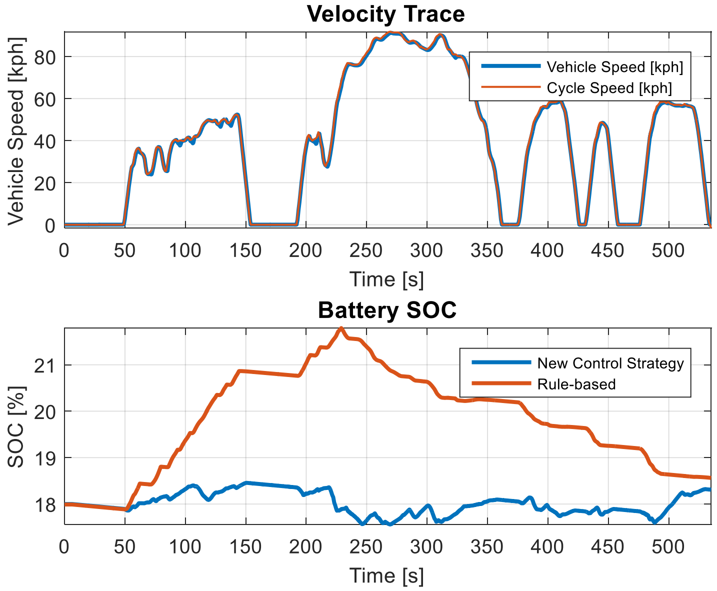


Figure 54 505 Drive Cycle and SOC profile

	Ruel Based Control	ECMS Control Strategy	Comparison
Fuel Consumption (L)	0.6013	0.5647	-7.1%
SOC-corrected fuel consumption (Wh/km)	612.02	568.57	
Delta SOC (%)	0.5732	0.3084	

Table 12 Energy Consumption Comparison for 505 drive cycle

5.6.2 US06Highway

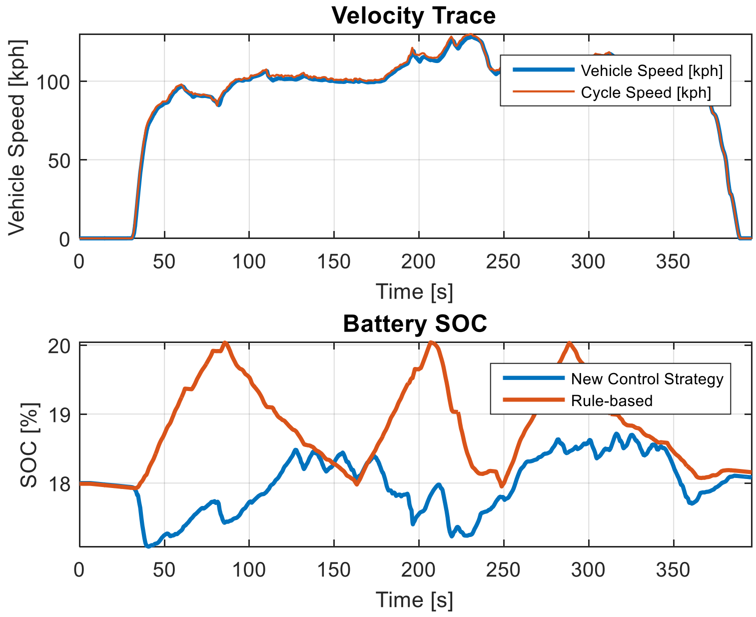


Figure 55 US06 Highway drive cycle and SOC profile

	Ruel Based Control	ECMS Control Strategy	Improvement
Fuel Consumption (L)	1.0368	0.9627	-8.5%
SOC-corrected fuel consumption (Wh/km)	626.41	573.20	
Delta SOC (%)	0.1669	0.082	

Table 13 Energy Consumption Comparison for US06 Highway drive cycle

5.6.3 US06 City

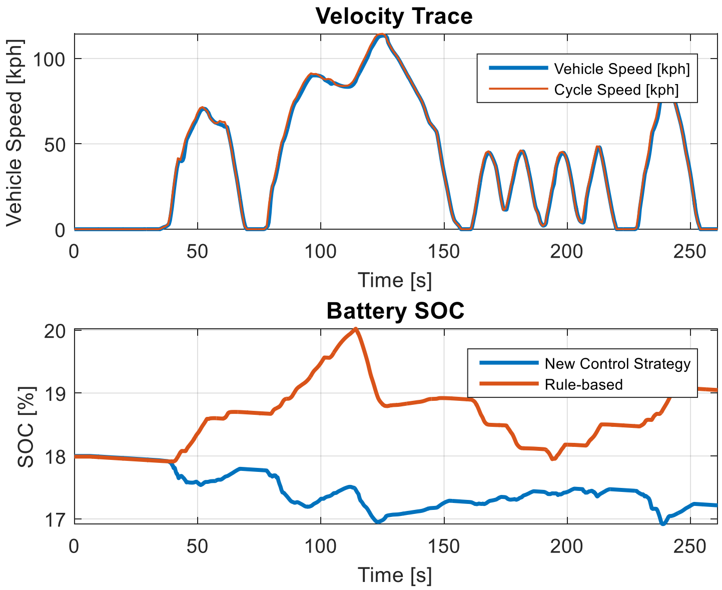


Figure 56 US06 City drive cycle and SOC profile

	Ruel Based Control	ECMS Control Strategy	Comparison
Fuel Consumption (L)	0.5502	0.4074	-5.7%
SOC-corrected fuel consumption (Wh/km)	1042.9	983.72	
Delta SOC (%)	1.06	-0.78%	

Table 14 Energy Consumption Comparison for US06 City drive cycle

5.6.4 HWFET Drive Cycle

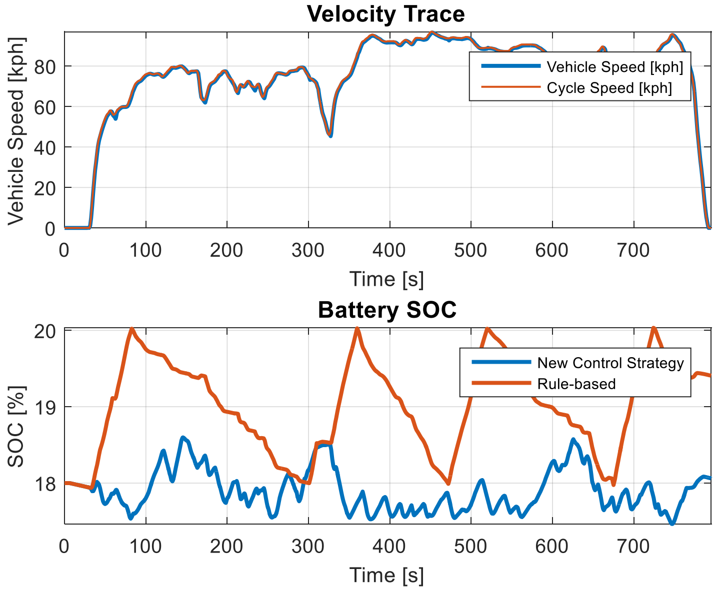


Figure 57 HWFET drive cycle and SOC profile

	Ruel Based Control	ECMS Control Strategy	Comparison
Fuel Consumption (L)	1.3018	1.22	-1.5%
SOC-corrected fuel consumption (Wh/km)	449.81	443.10	
Delta SOC (%)	1.41	0.06	

Table 15 Energy Consumption Comparison for HWFET drive cycle

5.6.5 Energy Consumption Comparison in E&EC event

A combination of rule-based for charge depleting mode and ECMS control strategy for charge sustaining mode was implemented in the hybrid supervisory controller in EcoCAR3 plant model simulator. The vehicle simulator was used to test different control strategies implemented in HSC and evaluate the effect that new control strategies would have on the overall vehicle energy consumption as well as fuel economy. In order to determine the new control strategy is effective or not, the energy consumption from new control strategy is compared to the energy consumption results from rule-based control strategy. In charge depleting mode, both rule-based control and ECMS based controller have the same control strategy, which is blended CD control strategy. In charge sustaining mode, the ECMS based controller had different control strategy from rule-based which is discussed in detail in chapter 4.

In order to compare the energy consumption between two control strategies under EcoCAR3 E&EC event, the vehicle simulator is used to run full E&EC drive cycles in both charge depleting mode and charge sustaining mode, the results for energy consumption for two control strategies are listed in table 16. Figure 58 shows the E&EC drive cycle for two control strategies and battery state of charge during the entire drive cycle. It's clearly that battery SOC sustains at targeted SOC level during CS mode with new control strategy, while rule-based control strategy oscillates under certain upper and lower SOC threshold.

Figure 60 and Figure 61 shows the engine operating points for two control strategies, one can see that most of engine operating points under new control strategy are within highest efficiency region, while for rule-based control strategy, most of operating points scattered.

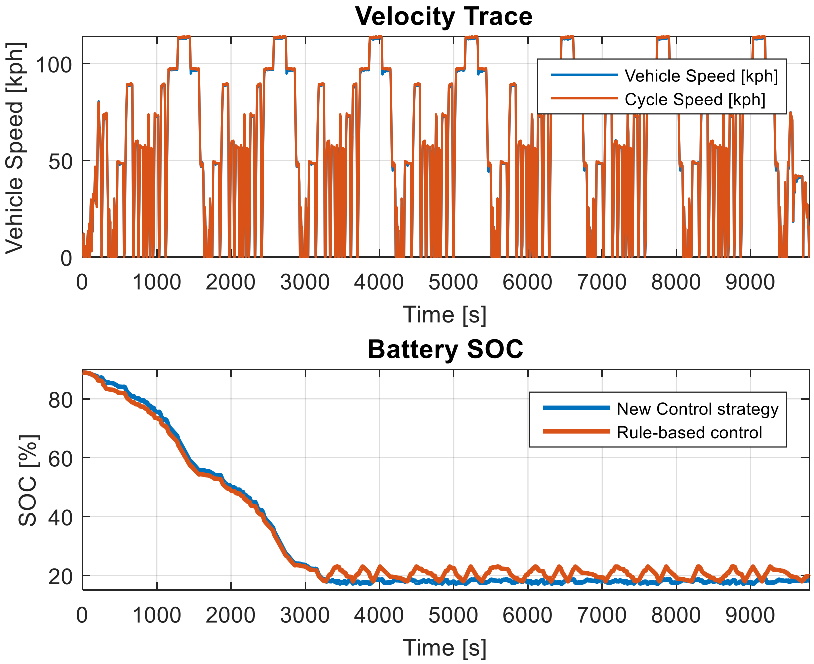


Figure 58 Three drive cycles speed trace and SOC profile

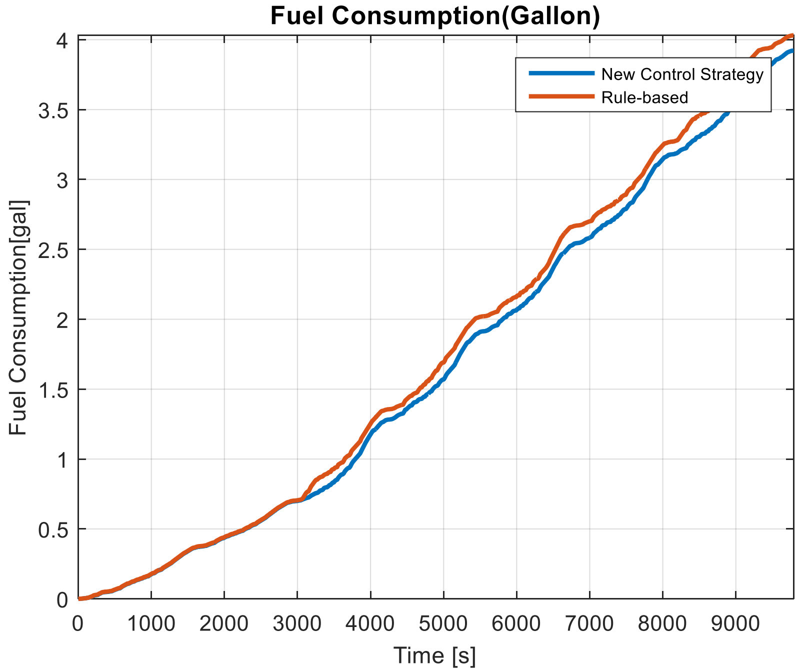
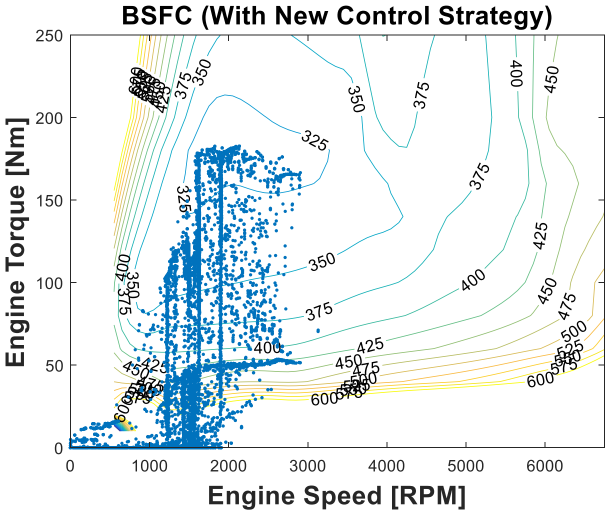


Figure 59 Engine fuel consumption



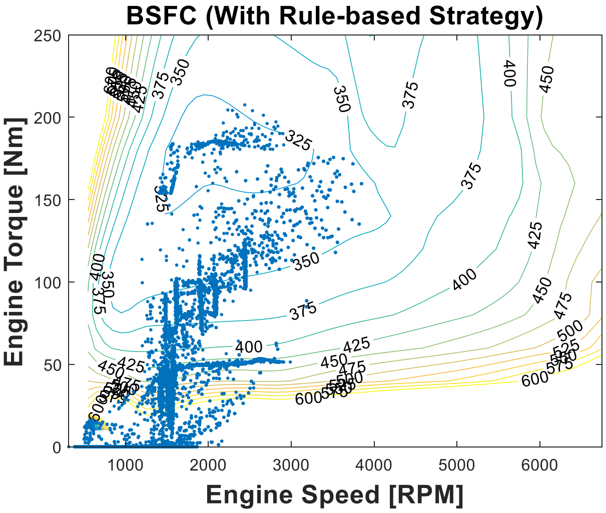


Figure 60Engine Operating Points with ECMS   Figure 61Engine Operating Points with Rule based Control

Table 16 below shows the vehicle energy consumption and fuel consumption for optimized and rule-based control strategies. The results show that optimized control strategy had fuel consumption of 3.92 gallon which is 9.9% decrease over rule- based control strategy, the optimized control strategy also had 563.43 Wh/km of UF-weighted energy consumption which is 7.4% decrease over rule-based control strategy while maintaining the SOC at targeted level. The decreases that optimized control strategy had make a significant difference on energy consumption for hybrid electric vehicles.

Table 16 Comparison of vehicle energy consumption for optimized and rule-based control strategies

	Ruel Based Control	ECMS Control Strategy	Improvement
Fuel Consumption (gal)	4.35	3.92	-9.9%
UF weighted Energy Consumption (Wh/km)	608.51	563.43	-7.4%
PEU WTW (Wh PE/km)	151.15	137.36	-9.1%
GHG WTW (g GHG/km)	170.85	158.33	-7.3%

6 Conclusion and Future Work

6.1 Conclusion

This study presents a detailed control strategies for hybrid supervisory controller of plug-in hybrid electric vehicles. Some techniques pertaining to control system development for clutch-less P2 architecture are briefly discussed in the thesis, like model based design, and software development process, V-cycle, which have great significant on development of vehicle control system.

A software development process was discussed in the thesis, which begins with the development of control requirements, referring to figure 7, V-cycle plays a significant role in developing control strategies for electric control units (ECUs). The requirements can be determined by the goal of competition and components interface, which are used for designing control system algorithms.

The control requirements developed in the thesis are mainly for developing hybrid supervisory controller (HSC), which is a high – level controller that interprets driver demand and controls interaction between powertrain components by their respective control units, it determines the appropriate torque split between two components as well as correct operating mode for hybrid electric vehicle. In this study, hybrid supervisory controller is divided into four parts: driver requested torque subsystem, mode selection and torque distribution, fault diagnostics as well as output. In torque distribution subsystem, the vehicle distributes the torque between engine and electric motor based on driver demanded power and current engine or electric motor power limits. This strategy is commonly used in automotive industry currently. The HSC is also able to perform diagnostics for all critical components to detect faults and mitigate faults as well as prevent faults. The clutch-less P2 architecture chosen by WSU EcoCAR 3 team leads to different control strategy in CD mode compared to normal P2 architecture, In CD mode, control strategy enables the engine always deliver limited torque so that the electric motor is not necessary to drag the engine for the sake of reducing total energy consumption, the electric motor produces the remaining torque to meet the driver requested torque. In CS mode, vehicle enables engine work at the highest efficient operation and extra torque produced is used to charge the battery to sustain the battery SOC.

The HSC algorithms implemented in the thesis is tested under WSU EcoCAR3 vehicle simulator in Model in the Loop (MIL), which contains all electric components and stock vehicle components modeled by Simulink as well as Simscape. The vehicle simulator is used to test effectiveness of control strategies in PHEV.

In addition, an optimized control strategy based on ECMS is proposed in the thesis, the charge depleting has the same control strategies with rule-based control strategy, since due to the limitation of clutch-less P2 architecture, the engine cannot be off when vehicle is in CD mode. The charge sustaining contains a different control strategy from rule-based control strategy. It optimizes the torque distribution between engine and electric motor in real time, as illustrated explicitly in chapter 5. To test the effectiveness of optimized control strategy for PHEV, the HSC with new control strategy was tested under EcoCAR3 vehicle simulator in MIL. Final results show that optimized control strategy had fuel consumption of 3.92 gallon which is 9.7% decrease over rule- based control strategy, the optimized control strategy also had 563.43 Wh/km of UF-weighted energy consumption which is 7.4% decrease over rule-based control strategy while maintaining the SOC at targeted level. Another advantage of this optimized control strategy is the sustainability of battery SOC whatever the drive conditions change. However, although optimized control strategy had lower fuel consumption during E&EC event, the algorithm runs in real time and evaluate each torque control variable at each time step which is computationally intensive when implementing this control strategy in real controller in the vehicle.

6.2 Discussion and Future Work

6.2.1 Validation

The optimized control strategy and rule based control strategy proposed in the thesis still need to be validated under hardware in the loop (HIL) and implemented in the vehicle’s controller. In the hardware in the loop environment, the HSC needs to be configured in the real controller and communicate with component controllers in dSPACE through CAN bus. This can be done before testing in the real vehicle. Once the HSC control strategy is validated in the HIL, the strategy will be transferred to the real vehicle, and this can be done by driving on the road and collecting data to compare with the results in the Simulink model.

6.2.2 Future Work

As mentioned previously, the emissions in hybrid electric vehicles is also an important criterion for evaluating the fuel economy of HEVs. However, the ECMS implemented in the thesis does not take emissions into consideration, which may cause the torque distribution strategy to be not optimal solutions. In order to optimize the torque distribution properly, the control strategy also needs to take consideration for transmission gear shifting which is also important control variable in energy management strategy. Therefore, those issues can be solved by multi-objective optimization strategy.

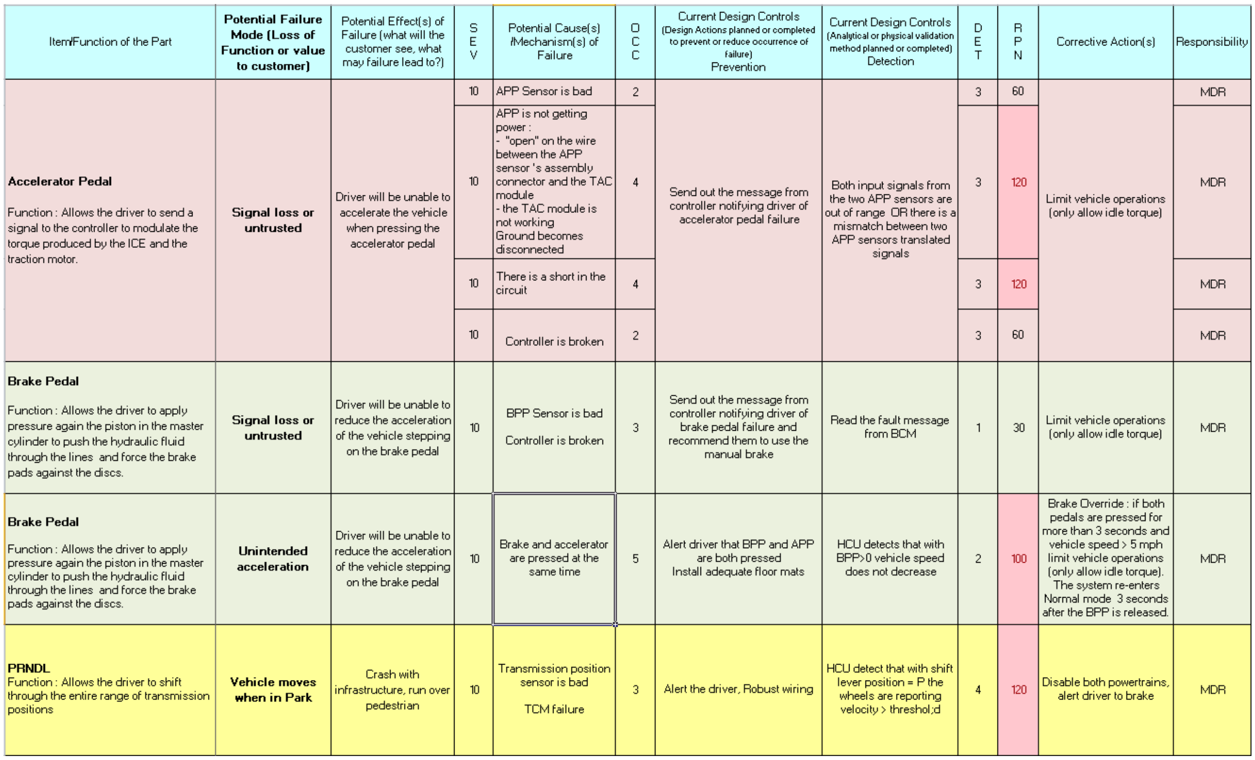
The huge disadvantage of the real-time optimized control strategy is computation time which may cause issues in the real controller when implemented the control strategy in the vehicle. To solve this problem, the control strategy can be optimized offline by perform simulation for all different kinds of drive cycle and create optimal torque distribution map as a function of various inputs, like driver torque demand, accelerator pedal position, engine speed, gear position, etc.

Appendix A

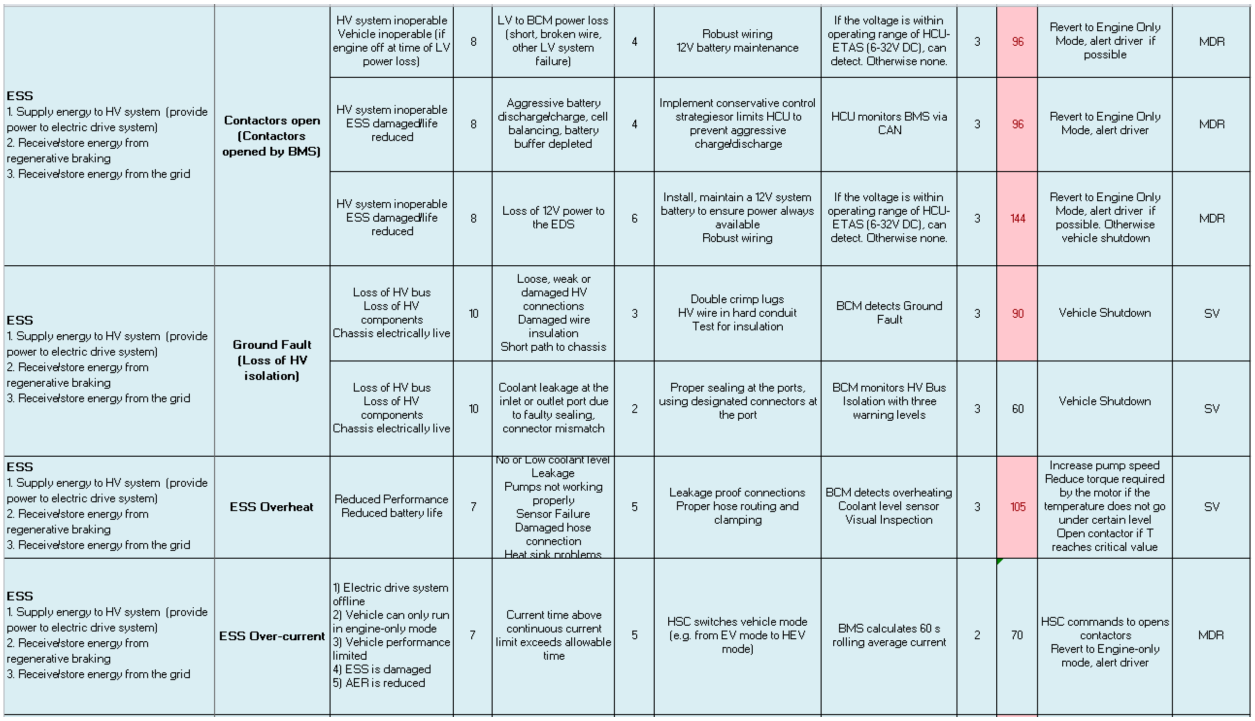
A.1 List of Abbreviations

AVTC	Advanced Vehicle Technology Competition
CD	Charge Depleting
CS	Charge Sustaining
E85	85% ethanol and 15% gasoline fuel by volume
EC	Energy consumption
ECMS	Equivalent Consumption Minimization Strategy
ECU	Electric Control Unit
EM	Electric Motor
E&EC	Emission and Energy Consumption
FC	Fuel Consumption
HIL	Hardware in the Loop
HSC	Hybrid Supervisory Controller
ICE	Internal Combustion Engine
MIL	Model in the Loop
PHEV	Plug-in Hybrid Electric Vehicle
SIL	Software in the Loop
SOC	State of Charge
UF	Utility factor
VIL	Vehicle in the Loop
VTS	Vehicle Technical Specification
WSU	Wayne State University

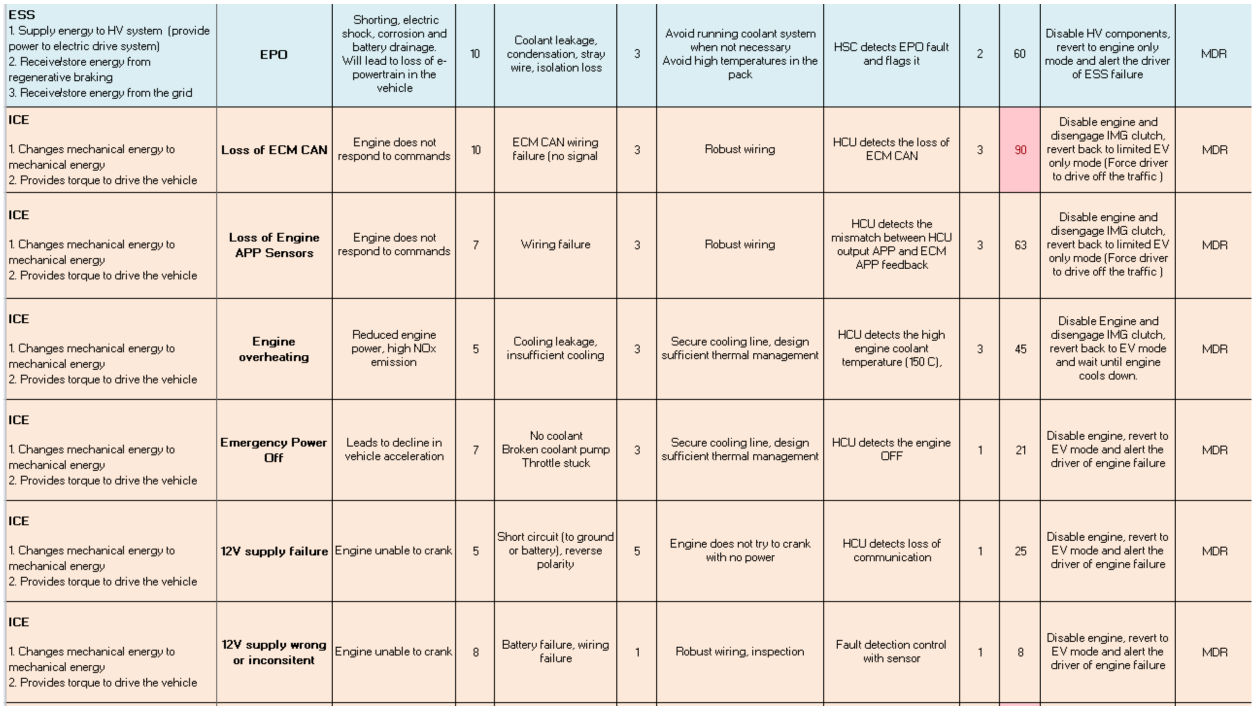
A.2 DFMEA



Item/Function of the Part	Potential Failure Mode (Loss of Function or value to customer)	Potential Effect(s) of Failure (what will the customer see, what may failure lead to?)	SEV	Potential Cause(s) /Mechanism(s) of Failure	OCC	Current Design Controls (Design Actions planned or completed to prevent or reduce occurrence of failure) Prevention	Current Design Controls (Analytical or physical validation method planned or completed) Detection	DET	RPN	Corrective Action(s)	Responsibility
Accelerator Pedal Function : Allows the driver to send a signal to the controller to modulate the torque produced by the ICE and the traction motor.	**Signal loss or untrusted**	Driver will be unable to accelerate the vehicle when pressing the accelerator pedal	10	APP Sensor is bad	2	Send out the message from controller notifying driver of accelerator pedal failure	Both input signals from the two APP sensors are out of range OR there is a mismatch between two APP sensors translated signals	3	60	Limit vehicle operations (only allow idle torque)	MDR
			10	APP is not getting power : - "open" on the wire between the APP sensor 's assembly connector and the TAC module - the TAC module is not working Ground becomes disconnected	4			3	120		MDR
			10	There is a short in the circuit	4			3	120		MDR
			10	Controller is broken	2			3	60		MDR
Brake Pedal Function : Allows the driver to apply pressure again the piston in the master cylinder to push the hydraulic fluid through the lines and force the brake pads against the discs.	**Signal loss or untrusted**	Driver will be unable to reduce the acceleration of the vehicle stepping on the brake pedal	10	BPP Sensor is bad Controller is broken	3	Send out the message from controller notifying driver of brake pedal failure and recommend them to use the manual brake	Read the fault message from BCM	1	30	Limit vehicle operations (only allow idle torque)	MDR
Brake Pedal Function : Allows the driver to apply pressure again the piston in the master cylinder to push the hydraulic fluid through the lines and force the brake pads against the discs.	**Unintended acceleration**	Driver will be unable to reduce the acceleration of the vehicle stepping on the brake pedal	10	Brake and accelerator are pressed at the same time	5	Alert driver that BPP and APP are both pressed Install adequate floor mats	HCU detects that with BPP>0 vehicle speed does not decrease	2	100	Brake Override : if both pedals are pressed for more than 3 seconds and vehicle speed > 5 mph limit vehicle operations (only allow idle torque). The system re-enters Normal mode 3 seconds after the BPP is released.	MDR
PRNDL Function : Allows the driver to shift through the entire range of transmission positions	**Vehicle moves when in Park**	Crash with infrastructure, run over pedestrian	10	Transmission position sensor is bad TCM failure	3	Alert the driver, Robust wiring	HCU detect that with shift lever position = P the wheels are reporting velocity > threshol;d	4	120	Disable both powertrains, alert driver to brake	MDR
PRNDL Function : Allows the driver to shift through the entire range of transmission positions	**Powertrain does not transmits torque only to the driven wheels when in Reverse**	Crash with infrastructure, run over pedestrian	10	Transmission position sensor is bad TCM failure	3	Alert the driver, Robust wiring	HCU detect that with shift lever position = R the non driven wheels are reporting velocity > threshold	4	120	Disable both powertrains, alert driver to brake	MDR
PRNDL Function : Allows the driver to shift through the entire range of transmission positions	**Vehicle does not move when in Drive**	Driver will be unable to accelerate the vehicle when pressing the accelerator pedal	10	Transmission position sensor is bad TCM failure	2	Alert the driver, Robust wiring	HCU detect that with shift lever position = D , APP > 5% and BPP not zero the vehicle speed is zero	5	100	Alert driver	MDR
Powertrain Torque Control Function : Manages and supervise the torque distribution and delivery	**Torque is delivered in the incorrect direction**	Unintended Acceleration/ Deceleration	10	HCU logic is incorrect	3	Robust algorithm implementation in the HSC, Robust wiring, Alert driver	HCU detects that the torque direction is not in agreement with the operational mode and driver equest	4	120	Disable inverter, diable regenerative braking	MDR
Powertrain Torque Control Function : Manages and supervise the torque distribution and delivery	**Vehicle movs in the incorrect direction**	Crash with infrastructure, run over pedestrian	10	HCU logic is incorrect, TCM failure	3	Robust algorithm implementation in the HSC, Robust wiring, Alert driver	HCU detects that the vehicle direction is not in agreement with driver equest	5	150	Vehicle Shutdown, Alert Driver	MDR
Powertrain Torque Control Function : Manages and supervise the torque distribution and delivery	**Torque is delivered while vehicle is charging from the grid**	Damage to the vehicle, Damage to the charger	10	HCU logic is incorrect	2	Robust algorithm implementation in the HSC	HCU detect that traction torque os produced while vehicle is charging from external charger	5	100	Vehicle Shutdown, Alert Driver	MDR
ESS 1. Supply energy to HV system (provide power to electric drive system) 2. Receive/store energy from regenerative braking 3. Receive/store energy from the grid	**Loss of BMS CAN**	HV system inoperable (Contactors automatically open)	8	BMS CAN wiring failure (no signal	5	Robust wiring	HCU detects the loss of BMS CAN	3	120	Revert to Engine Only Mode, alert driver	MDR

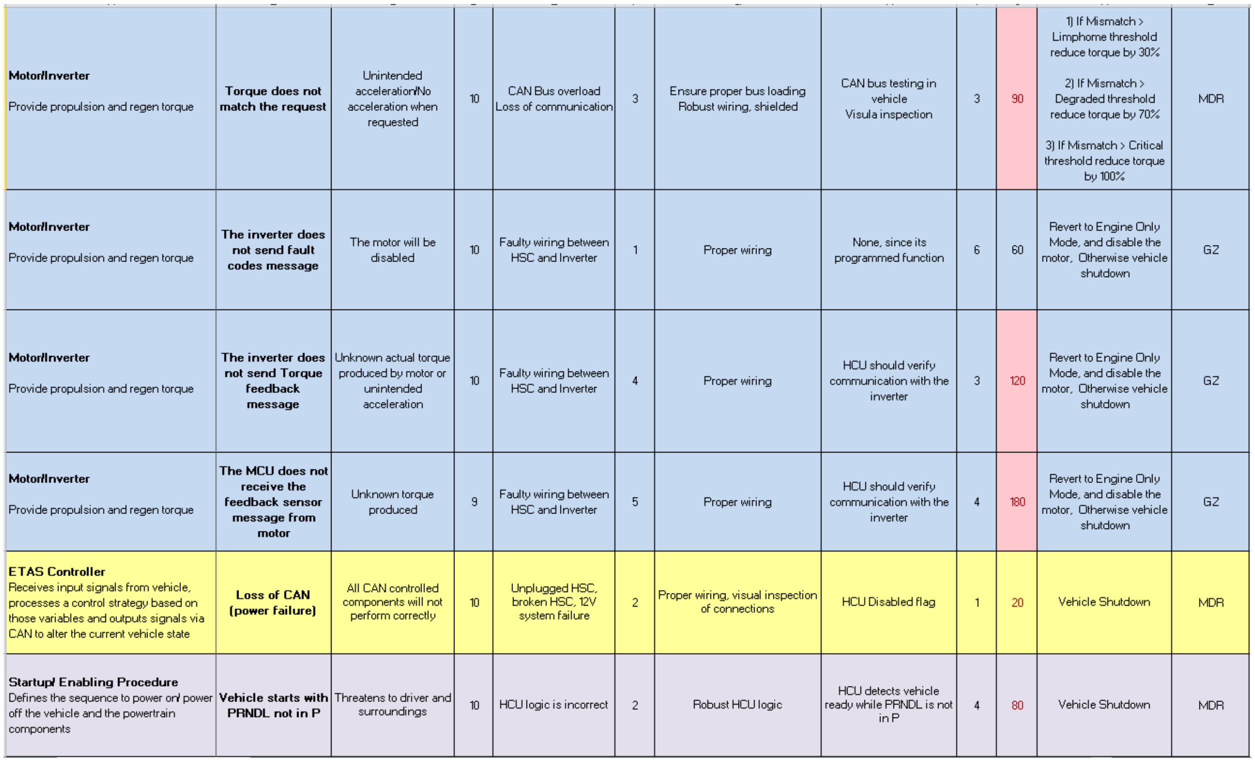


ESS 1. Supply energy to HV system (provide power to electric drive system) 2. Receive/store energy from regenerative braking 3. Receive/store energy from the grid	**Contactors open (Contactors opened by BMS)**	HV system inoperable Vehicle inoperable (if engine off at time of LV power loss)	8	LV to BCM power loss (short, broken wire, other LV system failure)	4	Robust wiring 12V battery maintenance	If the voltage is within operating range of HCU-ETAS (6-32V DC), can detect. Otherwise none.	3	96	Revert to Engine Only Mode, alert driver if possible	MDR
		HV system inoperable ESS damaged/life reduced	8	Aggressive battery discharge/charge, cell balancing, battery buffer depleted	4	Implement conservative control strategiesor limits HCU to prevent aggressive charge/discharge	HCU monitors BMS via CAN	3	96	Revert to Engine Only Mode, alert driver	MDR
		HV system inoperable ESS damaged/life reduced	8	Loss of 12V power to the EDS	6	Install, maintain a 12V system battery to ensure power always available Robust wiring	If the voltage is within operating range of HCU-ETAS (6-32V DC), can detect. Otherwise none.	3	144	Revert to Engine Only Mode, alert driver if possible. Otherwise vehicle shutdown	MDR
ESS 1. Supply energy to HV system (provide power to electric drive system) 2. Receive/store energy from regenerative braking 3. Receive/store energy from the grid	**Ground Fault (Loss of HV isolation)**	Loss of HV bus Loss of HV components Chassis electrically live	10	Loose, weak or damaged HV connections Damaged wire insulation Short path to chassis	3	Double crimp lugs HV wire in hard conduit Test for insulation	BCM detects Ground Fault	3	90	Vehicle Shutdown	SV
		Loss of HV bus Loss of HV components Chassis electrically live	10	Coolant leakage at the inlet or outlet port due to faulty sealing, connector mismatch	2	Proper sealing at the ports, using designated connectors at the port	BCM monitors HV Bus Isolation with three warning levels	3	60	Vehicle Shutdown	SV
ESS 1. Supply energy to HV system (provide power to electric drive system) 2. Receive/store energy from regenerative braking 3. Receive/store energy from the grid	**ESS Overheat**	Reduced Performance Reduced battery life	7	No or Low coolant level Leakage Pumps not working properly Sensor Failure Damaged hose connection Heat sink problems	5	Leakage proof connections Proper hose routing and clamping	BCM detects overheating Coolant level sensor Visual Inspection	3	105	Increase pump speed Reduce torque required by the motor if the temperature does not go under certain level Open contactor if T reaches critical value	SV
ESS 1. Supply energy to HV system (provide power to electric drive system) 2. Receive/store energy from regenerative braking 3. Receive/store energy from the grid	**ESS Over-current**	1) Electric drive system offline 2) Vehicle can only run in engine-only mode 3) Vehicle performance limited 4) ESS is damaged 5) AER is reduced	7	Current time above continuous current limit exceeds allowable time	5	HSC switches vehicle mode (e.g. from EV mode to HEV mode)	BMS calculates 60 s rolling average current	2	70	HSC commands to opens contactors Revert to Engine-only mode, alert driver	MDR



ESS 1. Supply energy to HV system (provide power to electric drive system) 2. Receive/store energy from regenerative braking 3. Receive/store energy from the grid	**EPO**	Shorting, electric shock, corrosion and battery drainage. Will lead to loss of e-powertrain in the vehicle	10	Coolant leakage, condensation, stray wire, isolation loss	3	Avoid running coolant system when not necessary Avoid high temperatures in the pack	HSC detects EPO fault and flags it	2	60	Disable HV components, revert to engine only mode and alert the driver of ESS failure	MDR
ICE 1. Changes mechanical energy to mechanical energy 2. Provides torque to drive the vehicle	**Loss of ECM CAN**	Engine does not respond to commands	10	ECM CAN wiring failure (no signal	3	Robust wiring	HCU detects the loss of ECM CAN	3	90	Disable engine and disengage IMG clutch, revert back to limited EV only mode (Force driver to drive off the traffic)	MDR
ICE 1. Changes mechanical energy to mechanical energy 2. Provides torque to drive the vehicle	**Loss of Engine APP Sensors**	Engine does not respond to commands	7	Wiring failure	3	Robust wiring	HCU detects the mismatch between HCU output APP and ECM APP feedback	3	63	Disable engine and disengage IMG clutch, revert back to limited EV only mode (Force driver to drive off the traffic)	MDR
ICE 1. Changes mechanical energy to mechanical energy 2. Provides torque to drive the vehicle	**Engine overheating**	Reduced engine power, high NOx emission	5	Cooling leakage, insufficient cooling	3	Secure cooling line, design sufficient thermal management	HCU detects the high engine coolant temperature (150 C),	3	45	Disable Engine and disengage IMG clutch, revert back to EV mode and wait until engine cools down.	MDR
ICE 1. Changes mechanical energy to mechanical energy 2. Provides torque to drive the vehicle	**Emergency Power Off**	Leads to decline in vehicle acceleration	7	No coolant Broken coolant pump Throttle stuck	3	Secure cooling line, design sufficient thermal management	HCU detects the engine OFF	1	21	Disable engine, revert to EV mode and alert the driver of engine failure	MDR
ICE 1. Changes mechanical energy to mechanical energy 2. Provides torque to drive the vehicle	**12V supply failure**	Engine unable to crank	5	Short circuit (to ground or battery), reverse polarity	5	Engine does not try to crank with no power	HCU detects loss of communication	1	25	Disable engine, revert to EV mode and alert the driver of engine failure	MDR
ICE 1. Changes mechanical energy to mechanical energy 2. Provides torque to drive the vehicle	**12V supply wrong or inconsitent**	Engine unable to crank	8	Battery failure, wiring failure	1	Robust wiring, inspection	Fault detection control with sensor	1	8	Disable engine, revert to EV mode and alert the driver of engine failure	MDR

ICE 1. Changes mechanical energy to mechanical energy 2. Provides torque to drive the vehicle	**Torque mismatch**	Uninended Acceleration / Deceleration	10	ECM Communication broken, Power reduced	5	Robust wiring, RAC check, Heartbeat check	HCU detects toque mismatch	2	100	1) If Mismatch > Limphome threshold reduce torque by 30% 2) If Mismatch > Degraded threshold reduce torque by 70% 3) If Mismatch > Critical threshold reduce torque by 100%	MDR
ICE 1. Changes mechanical energy to mechanical energy 2. Provides torque to drive the vehicle	**Over-speed**	Unintended acceleration/ Damage to the engine, damage to the motor	10	ECM communication loss, HCU limits not in place/not calibrated properly, wiring failure	3	Robust wiring, Saturations in the HSC, Signal Plausibility check	HCU detects over-speed	3	90	Shutdown the engine	MDR
Transmission 1. Tramsmit the torque from engine to final drive 2. Extend the range of engine speed and torque to meet the driving demands 3. Improve the drivability and performance of the vehicle as well as reduce the emission	**Loss of TCM CAN**	Transmission does not respond to commands	10	TCM CAN wiring failure	2	Robust wiring	HCU detects the loss of TCM CAN	3	60	Disengage IMG clutch, revert back to limited EV only mode (Force driver to drive off the traffic)	MDR
Transmission 1. Tramsmit the torque from engine to final drive 2. Extend the range of engine speed and torque to meet the driving demands 3. Improve the drivability and performance of the vehicle as well as reduce the emission	**Clutch is locked but will not engage**	Engine rpm will rev higher than expected during shifting (increased emissions/en consumption) Clutch wearing, transmission failure	10	Worn clutch used in shifting event	4	None	HSC Rationality Diagnostic : check expeced shift time vs actual shift time Check for expected rpm levels during shift	4	160	Send out a message from HSC notifying driver of gear shift automatically	MDR
Motor/Inverter Provide propulsion and regen torque	**The Motor shaft is not concentric and fails to transmit desired torque**	loss the motor power and performance	10	Improper alignment within vehicle with improper spline specifications for rated torque	3	None	Vehicle Testing	4	120	Shut down the vehicle	GZ
Motor/Inverter Provide propulsion and regen torque	**Loss of MCU CAN**	Local : Inverter continues to function of last received message Global : Undesired motor torque when braking/accelerating	9	CAN bus overload	3	MCU CAN heartbeat monitoring	HCU detects the loss of MCU CAN	4	108	Revert to Engine Only Mode, and disable the motor, Otherwise vehicle shutdown	MDR
		Local : Inverter continues to function of last received message Global : Undesired motor torque when braking/accelerating	9	MCU CAN wiring failure	2	Robust wiring	HCU detects the loss of MCU CAN Visual Inspection	4	72	Revert to Engine Only Mode, and disable the motor, Otherwise vehicle shutdown	GZ
Motor/Inverter Provide propulsion and regen torque	**Motor Overheating**	Reduce the motor power and performance; reduce the motor life	8	No or Low coolant level Leakage Pumps not working properly Sensor Failure Damaged hose connection Heat sink problems	3	Leakage proof connections Proper hose routing and clamping	MCU detects overheating Coolant level sensor Visual Inspection	3	72		
Motor/Inverter Provide propulsion and regen torque	**Inverter Overheating**	Reduce the inverter performance; reduce inverter life	8	No or Low coolant level Leakage Pumps not working properly Sensor Failure Damaged hose connection Heat sink problems	5	Leakage proof connections Proper hose routing and clamping	MCU detects overheating Coolant level sensor Visual Inspection	4	160	Revert to Engine Only Mode, and disable the motor, alert driver if possible. Otherwise vehicle shutdown	GZ
Motor/Inverter Provide propulsion and regen torque	**Inverter Over-Voltage**	Inverter is disabled, Torque Mismatch, Unintended Decel	8	Battery voltage too high	7	Limit battery voltage to 419 V	Monitor Lock-out signal from MCU	3	168	Provide driver torque with the engine if possible. Otherwise coastdown. Alert driver	MDR
Motor/Inverter Provide propulsion and regen torque	**Inverter does not receive enough voltage to enable power mode**	Inverter is not enabled	6	Faulty wiring between ESS and Inverter	5	Robust wiring	Vehicle Testing	6	180	Revert to Engine Only Mode	GZ



Motor/Inverter Provide propulsion and regen torque	**Torque does not match the request**	Unintended acceleration/No acceleration when requested	10	CAN Bus overload Loss of communication	3	Ensure proper bus loading Robust wiring, shielded	CAN bus testing in vehicle Visula inspection	3	90	1) If Mismatch > Limphome threshold reduce torque by 30% 2) If Mismatch > Degraded threshold reduce torque by 70% 3) If Mismatch > Critical threshold reduce torque by 100%	MDR
Motor/Inverter Provide propulsion and regen torque	**The inverter does not send fault codes message**	The motor will be disabled	10	Faulty wiring between HSC and Inverter	1	Proper wiring	None, since its programmed function	6	60	Revert to Engine Only Mode, and disable the motor, Otherwise vehicle shutdown	GZ
Motor/Inverter Provide propulsion and regen torque	**The inverter does not send Torque feedback message**	Unknown actual torque produced by motor or unintended acceleration	10	Faulty wiring between HSC and Inverter	4	Proper wiring	HCU should verify communication with the inverter	3	120	Revert to Engine Only Mode, and disable the motor, Otherwise vehicle shutdown	GZ
Motor/Inverter Provide propulsion and regen torque	**The MCU does not receive the feedback sensor message from motor**	Unknown torque produced	9	Faulty wiring between HSC and Inverter	5	Proper wiring	HCU should verify communication with the inverter	4	180	Revert to Engine Only Mode, and disable the motor, Otherwise vehicle shutdown	GZ
ETAS Controller Receives input signals from vehicle, processes a control strategy based on those variables and outputs signals via CAN to alter the current vehicle state	**Loss of CAN (power failure)**	All CAN controlled components will not perform correctly	10	Unplugged HSC, broken HSC, 12V system failure	2	Proper wiring, visual inspection of connections	HCU Disabled flag	1	20	Vehicle Shutdown	MDR
Startup/ Enabling Procedure Defines the sequence to power on/ power off the vehicle and the powertrain components	**Vehicle starts with PRNDL not in P**	Threatens to driver and surroundings	10	HCU logic is incorrect	2	Robust HCU logic	HCU detects vehicle ready while PRNDL is not in P	4	80	Vehicle Shutdown	MDR

A.3 Test cases Documents for safety critical algorithms

Test Case Overview	**<APP1 and APP2 mismatch>**		
Priority:	High	Version:	1.0
Test Platform:	MIL, SIL, HIL	Last Updated:	11/4/2016
DFMEA Number:		Author:	Guilin Zhu
Test Case Description:	The test simulates the case in which there is a mismatch fault between APP1 and APP2. When the pedal position value of the two sensors does not agree within 1%, the *Drv_APP_Agree* and *APP_Valid* sets to 0. To implement the fault, *Mismatch_APP_ON*will be implemented into*APP_Fault_Insertion block*, and when the fault triggers, *APP2 signal* will be set to *cal.APP.Mismatch_Value+0.01* value. To perform this test, the tester needs to set the mismatch fault for *APP1 and APP2* before running the simulation and the fault will be implemented by running fault script. Once the simulation is complete the tester will compare the obtained results with the expected results to determine if the test is passed. The test is considered "passed" when the simulation results match the expected results.		
Test Case Procedure			
Test Initialization:	1)under the Input Conversions->DriverInput_Conversions-> Override APP1 (%), set control port to 0 2) under the Input Conversions->DriverInput_Conversions-> Override APP (%)2, set control port to 0. 3) Select the 505 drive cycle from the GUI 4) Set SOC to 90% from the GUI in order to run CD mode as default mode. 5) Run initial fileMain_init.m to initialize the model parameters		

Test Body:	1) Run Fault_Trigger.m to insert the fault, and *Mismatch_APP_ON*(under Plant Actuators -> Analog ->APP_Fault_Insertion) will set to 1 and all other faults will be 0 when fault triggers 2) Run the model 3) Check the results obtained in the Scope block for each fault
Test Completion:	1)Record the result 2)Restore the original state of model 3) Run Fault_Clean.m to clean the APP_Mismatch fault
Test Case Summary	
Expected Results:	***Pass/Fail criteria:*** *CD mode:* *1) Vehicle speed=0;* *2) Motor torque output =0;* *Engine-Only mode:* *1) Vehicle speed=0;* *2) Engine torque output=0;* - *Under the Signal diagnostic-> Driver signal diagnostic, Drv_APP_Agree* will be 0, and ->systemDiag->eSystemDiagnostics, eSystemStatus will be 0 and icsSystemStatus will also be 0; - *Under Camaro Plant Model ->Chassis, chas_lin_spd_out, the speed of vehicle will go to 0;* - *Under Camaro Plant Model->IMG->IMG Plant->Electric Machine, mot_trq_out will be 0;*

Test Case Overview	**<APP1 and APP2 Out of range>**		
Priority:	High	Version:	1.0
Test Platform:	MIL, SIL, HIL	Last Updated:	11/4/2016
DFMEA Number:		Author:	Guilin Zhu
Test Case Description:	The test simulates the case in which there is an out-of-range fault between APP1 and APP2. When the pedal position value of the two sensors exceed a critical threshold, the *Drv_APP1_[%]_SigValid orDrv_APP2_[%]_SigValid*set to 0. To implement the fault, *APP1_OOR_ON and APP2_OOR_ON* will be implemented into*APP_Fault_Insertion block*, and when the fault triggers, *APP1 or APP2 signal* will be set to *cal.APP1.IN_Max_SC_Prcnt+1* value. To perform this test, the tester needs to set out-of-range fault for *APP1 or APP2* before running the simulation and the fault will be implemented by running fault script. Once the simulation is complete the tester will compare the obtained results with the expected results to determine if the test is passed. The test is considered "passed" when the simulation results match the expected results.		
Test Case Procedure			
Test Initialization:	1)under the Input Conversions->DriverInput_Conversions-> Override APP1 (%), set control port to 0 2) under the Input Conversions->DriverInput_Conversions-> Override APP (%)2, set control port to 0, and override all other signals 3) Select the 505 drive cycle from the GUI 4) Set SOC to 90% from the GUI in order to run CD mode as default mode.		

	5) Run initial fileMain_init.m to initialize the model parameters
Test Body:	1) Run Fault_Trigger.m to insert the fault, and *APP1_OOR_ON or APP2_OOR_ON* (under Plant Actuators -> Analog ->APP_Fault_Insertion) will set to 1 and all other faults will be 0 when fault triggers 2) Run the model 3) Check the results obtained in the Scope block for each fault
Test Completion:	1)Record the result 2)Restore the original state of model 3) Run Fault_Clean.m to clean the APP_OOR fault
Test Case Summary	
Expected Results:	***Pass/Fail criteria:*** *CD mode:* *3) Vehicle speed=0;* *4) Motor torque output =0;* *Engine-Only mode:* *3) Vehicle speed=0;* *4) Engine torque output=0;* • *Under the Signal diagnostic-> Driver signal diagnostic, Drv_APP1_[%]_SigValid or Drv_APP2_[%]_SigValid*will be 0, and ->systemDiag->eSystemDiagnostics, eSystemStatus will be 0 and icsSystemStatus will also be 0; • *Under Camaro Plant Model ->Chassis, chas_lin_spd_out, the speed of vehicle will go to 0;* • *Under Camaro Plant Model->IMG->IMG Plant->Electric Machine, mot_trq_out will be 0;*

Test Case Overview	**<BPP Fault>**		
Priority:	High	Version:	1.0
Test Platform:	MIL, SIL, HIL	Last Updated:	11/4/2016
DFMEA Number:		Author:	Guilin Zhu
Test Case Description:	The test simulates the case in which the brake pedal is depressed but the vehicle fails to decelerate at an acceptable rate. When the commanded BPP (%) failed to produce acceptable deceleration values or vehicle deceleration is 0 when BPP>0, then the *Brake_Failed*flagsets to 1. To implement the fault, *BPP Fault will be inserted into the Chassis block*. When the BPP fault is triggered, the vehicle acceleration which is *chas_plant_lin_accel* will be set to 1/10 of original value, therefore the vehicle will fail to decelerate at an acceptable value. To perform this test, the tester needs to set fault for *BPP* before running the simulation and the fault will be implemented by running fault script. Once the simulation is complete the tester will compare the obtained results with the expected results to determine if the test is passed. The test is considered "passed" when the simulation results match the expected results.		
Test Case Procedure			
Test Initialization:	1) under the Input Conversions->DriverInput_Conversions-> Override BPP (%), set control port to 0.		

	2) under*Camaro Fault Detection->Input Conversions*, override all other signals to normal value. 3) Select the 505 drive cycle from the GUI 4) Set SOC to 90% from the GUI in order to run CD mode as default mode. 5) Run initial fileMain_init.m to initialize the model parameters
Test Body:	1) Run Fault_Trigger.m to insert the fault, and *BPP_Flt*(under Camaro Plant Model-> Chassis) will set to 1. 2) Run the model 3) Check the results obtained in the Scope block for each fault
Test Completion:	1)Record the result 2)Restore the original state of model 3) Run Fault_Clean.m to clean the BPP_Flt fault
Test Case Summary	
Expected Results:	***Pass/Fail criteria:*** *1) Vehicle speed=0;* *2) Motor torque output/Engine torque output =0;* • *Under the Signal diagnostic-> Driver signal diagnostic, Brak_Failed* will be 1, and ->systemDiag->eSystemDiagnostics, eSystemStatus will be 0 and icsSystemStatus will also be 0; • *Under Camaro Plant Model ->Chassis, chas_lin_spd_out, the speed of vehicle will go to 0;* • *Under Camaro Plant Model->IMG->IMG Plant->Electric Machine, mot_trq_out will be 0;*

Test Case Overview	**<PRNDL Fault>**		
Priority:	High	Version:	1.0
Test Platform:	MIL, SIL, HIL	Last Updated:	11/4/2016
DFMEA Number:		Author:	Guilin Zhu
Test Case Description:	The test simulates the case in which the actual and commanded shift state is not the same (i.e. commanded state is park, but the vehicle is in drive). When the commanded shift state (*ShftLvrPos*) does not agree with the actual shift state (*TransEstGear*), the propulsive net torque will be set to 0, PRNDL shift failed then sets to 1. To implement the fault, *PRNDL Fault will be inserted into the Camaro Plant Model->Transmission block*. When commanded shift lever position is in Park, drive or reserve, the fault actual shift state would set to be drive, reverse, and drive which may cause severe accidents, then the PRNDL_shift_failed will be 1 and vehicle will be shut down. To perform this test, the tester needs to set fault for *PRNDL fault* before running the simulation and the fault will be implemented by running fault script. Once the simulation is complete the tester will compare the obtained results with the expected results to determine if the test is passed. The test is considered “passed” when the simulation results match the expected results.		
Test Case Procedure			
Test Initialization:	1) under the Input Conversions->DriverInput_Conversions-> Override LvrPosTrnsShft, set control port to 0. 2) under*Camaro Fault Detection->Input Conversions->TransEstGear*, set control port to 0, override all other signals to normal value.		

	3) Select the 505 drive cycle from the GUI 4) Set SOC to 90% from the GUI in order to run CD mode as default mode. 5) Run initial fileMain_init.m to initialize the model parameters
Test Body:	1) Run Fault_Trigger.m to insert the fault, and *PRNDL_Flt*(under Camaro Plant Model-> Transmission) will set to 1. 2) Run the model 3) Check the results obtained in the Scope block for each fault
Test Completion:	1)Record the result 2)Restore the original state of model 3) Run Fault_Clean.m to clean the PRNDL_Flt fault
Test Case Summary	
Expected Results:	***Pass/Fail criteria:*** *1) Vehicle speed=0;* *2) Motor torque output/Engine torque output =0;* • *Under the Signal diagnostic-> Driver signal diagnostic, PRNDL_shift_failed* will be 1, and ->systemDiag->eSystemDiagnostics, eSystemStatus will be 0 and icsSystemStatus will also be 0; • *Under Camaro Plant Model ->Chassis, chas_lin_spd_out, the speed of vehicle will go to 0;* • *Under Camaro Plant Model->IMG->IMG Plant->Electric Machine, mot_trq_out will be 0;*

Test Case Overview	**<Loss of CAN>**		
Priority:	High	Version:	1.0
Test Platform:	MIL, SIL, HIL	Last Updated:	10/29/2016
DFMEA Number:		Author:	Guilin Zhu
Test Case Description:	The test simulates the case in which there is loss of component CAN communication. Faults that occur include overruns, timeouts, and data mismatch Alive Rolling Counters (ARC) are used as software watchdogs to determine if a component is still communicating on the CAN network. In this test, we can only test the case that loss of MCU CAN. When the loss of CAN fault happens, the propulsive net torque will also be set to 0, MCURollingAliveActive then sets to 0. To implement the fault, *Loss of CAN Fault will be inserted into the Camaro Plant Model->IMG->Electric machine->Soft MCU*. When MCU_CAN_fault is inserted, data mismatch occurs when the ARC sent by the component do not match the ARC expected by the HSC, so the motor and MCU will be disabled, eSystemStatus will be offline, the vehicle thus will be shutdown. To perform this test, the tester needs to set fault for *Loss of CAN fault* before running the simulation and the fault will be implemented by running fault script. Once the simulation is complete the tester will compare the obtained results with the expected results to determine if the test is passed. The test is considered "passed" when the simulation results match the expected results.		
Test Case Procedure			
Test Initialization:	1) under the Input Conversions->MCU_Conversions-> Override rollingAliveCnt [123], set control port to 0.		

	2) under*Camaro Fault Detection->Input Conversions*, override all other signals to normal value. 3) Select the 505 drive cycle from the GUI 4) Set SOC to 90% from the GUI in order to run CD mode as default mode. 5) Run initial fileMain_init.m to initialize the model parameters
Test Body:	1) Run Fault_Trigger.m to insert the fault, and MCU_CAN_fault (under Camaro Plant Model-> IMG->Electric Machine->Soft MCU) will set to 1. 2) Run the model 3) Check the results obtained in the Scope block for each fault
Test Completion:	1)Record the result 2)Restore the original state of model 3) Run Fault_Clean.m to clean the MCU_CAN_fault
Test Case Summary	
Expected Results:	***Pass/Fail criteria:*** *1) Motor torque output =0;* *2) MCU_Status=0;* *3) eSystemStatus=0; iceSystemStatus=2;* *4) Vehicle mode switch to Engine only mode from CD mode;* - *Under the Signal diagnostic-> Mot signal diagnostic, MCURollingAliveActive*will be 0, and ->systemDiag->eSystemDiagnostics, eSystemStatus will be 0 and iceSystemStatus will be 1 when loss of MCU CAN triggers; - *Under HSC ->Powertrain Manager->Torque Distribution, the vehicle mode will change from 1 to 5 which is Engine only mode;* - *Under Camaro Plant Model->IMG->IMG Plant->Electric Machine, mot_trq_out will be 0;*

Test Case Overview	**<Motor Torque Mismatch>**		
Priority:	High	Version:	1.0
Test Platform:	MIL, SIL, HIL	Last Updated:	10/29/2016
DFMEA Number:		Author:	Guilin Zhu
Test Case Description:	The test simulates the case in which there is a torque mismatch between torque command from HSC and torque feedback from MCU. There are three levels of torque mismatch which are torque degraded, limphome and critical error level, and mitigation strategy thus will be different for each of them. When the Motor torque mismatch fault happens, the fault mitigation strategy under *Torque Distribution* block will take actions based on types of torque mismatch under fault detection block, if motor torque mismatch occurs, *MCU_Torque_Mismch will be set to 1.* To implement the fault, *Motor torque mismatch fault will be inserted into the Camaro Plant Model->IMG->Electric machine->mot_trq_out*. When *MCU_Torque_Mismch*is inserted, the motor torque output will be altered and do not match the commanded torque from HSC, so the fault will be detected by the Fault Detection block, then eSystemStatus will be offline or limited based on the types of torque mismatch fault, remedial actions will be in place.		

	To perform this test, the tester needs to set fault for *motor torque mismatch fault* before running the simulation and the fault will be implemented by running fault script. Once the simulation is complete the tester will compare the obtained results with the expected results to determine if the test is passed. The test is considered "passed" when the simulation results match the expected results.
Test Case Procedure	
Test Initialization:	1) under the Input Conversions->MCU_Conversions-> Override MCUTrqCmd_Nm, set control port to 0. 2) under*Camaro Fault Detection->Input Conversions->Torq_Feedback*, et control port to 0. 3) Select the 505 drive cycle from the GUI 4) Set SOC to 90% from the GUI in order to run CD mode as default mode. 5) Run initial fileMain_init.m to initialize the model parameters
Test Body:	1) Run Fault_Trigger.m to insert the fault, and MotTrqMismatch (under Camaro Plant Model-> IMG->Electric Machine) will be set to corresponding mismatch value based on mismatch types. 2) Run the model 3) Check the results obtained in the Scope block for each fault
Test Completion:	1)Record the result 2)Restore the original state of model 3) Run Fault_Clean.m to clean the MotTrqMismatch
Test Case Summary	
Expected Results:	***Pass/Fail criteria (Mismatch type=1/2):*** *1) MCU_Status=1;* *2) eSystemStatus=1;* *3) mot_trq_out will be limited to corresponding limited torque.* *1)Under the Component diagnostic-> Motor component diagnostic, MCU_Torque_Mismch*will be 1, and ->systemDiag->eSystemDiagnostics, eSystemStatus will be 1 when fault triggers; *2)Under Camaro Plant Model->IMG->IMG Plant->Electric Machine, mot_trq_out will be 0;* ***Pass/Fail criteria (Mismatch type=3):*** *1) Motor torque output =0;* *2) MCU_Status=0;* *3) eSystemStatus=0; iceSystemStatus=2;* *4) Vehicle mode switch to Engine only mode from CD mode;* • *Under the Component diagnostic-> Motor component diagnostic, MCU_Torque_Mismch*will be 1, and ->systemDiag->eSystemDiagnostics, eSystemStatus will be 0 and iceSystemStatus will be 1 when fault triggers; • *Under HSC ->Powertrain Manager->Torque Distribution, the vehicle mode will change from 1 to 5 which is Engine only mode;* • *Under Camaro Plant Model->IMG->IMG Plant->Electric Machine, mot_trq_out will be 0;*

Test Case Overview	**<Torque Direction Mismatch>**		
Priority:	High	Version:	1.0

Test Platform:	MIL, SIL, HIL	Last Updated:	11/12/2016
DFMEA Number:		Author:	Guilin Zhu
Test Case Description:	The test simulates the case in which there is a regenerative braking torque direction mismatch, result in propulsion rather than braking. When the regenerative braking torque direction mismatch happens, *Regen_Torque_Dir will be set to 1.* To implement the fault, *Regen_Torque_Dir will be inserted into the Camaro Plant Model->IMG->Electric machine.* When *Regen_Torque_Dir fault* is inserted, the motor torque command will be altered when the vehicle is required to use regenerative braking system however the vehicle will have unintended acceleration, so the fault will be detected by the Fault Detection block, eSystemStatus will be limited, and regenerative braking system will be disabled. To perform this test, the tester needs to set fault for *Regen_Torque_Dir fault* before running the simulation and the fault will be implemented by running fault script. Once the simulation is complete the tester will compare the obtained results with the expected results to determine if the test is passed. The test is considered "passed" when the simulation results match the expected results.		
Test Case Procedure			
Test Initialization:	1) under the Input Conversions->MCU_Conversions-> Override MCUTrqCmd_Nm, set control port to 0. 2) under*Camaro Fault Detection->Input Conversions->Torq_Feedback,* set control port to 0. 3) under*Camaro Fault Detection->Input Conversions, override all other signals to normal value.* 4) Select the 505 drive cycle from the GUI 5) Set SOC to 90% from the GUI in order to run CD mode as default mode. 6) Run initial fileMain_init.m to initialize the model parameters		
Test Body:	1) Run Fault_Trigger.m to insert the fault, and *Regen_Torque_Dir* (under Camaro Plant Model-> IMG->Electric Machine) will be set to corresponding mismatch value based on mismatch types. 2) Run the model 3) Check the results obtained in the Scope block for each fault		
Test Completion:	1)Record the result 2)Restore the original state of model 3) Run Fault_Clean.m to clean the *Regen_Torque_Dir*		
Test Case Summary			
Expected Results:	***Pass/Fail criteria:*** *1) MCU_Status=1;* *2) eSystemStatus=1;* *3) Regenerative braking system will be disabled.* • *Under the Component diagnostic-> Motor component diagnostic, Regen_Torque_Dir* Mismatch will be 1, and ->systemDiag->eSystemDiagnostics, eSystemStatus will be 1 when fault triggers; • *Under Camaro Plant Model->IMG->IMG Plant->Electric Machine, negative torque output will be 0;*		

Test Case Overview	**<Vehicle Direction Fault>**		
Priority:	High	Version:	1.0
Test Platform:	MIL, SIL, HIL	Last Updated:	11/4/2016
DFMEA Number:		Author:	Guilin Zhu
Test Case Description:	The test simulates the case in which the vehicle does not move in the intended direction when in drive gear. The propulsive net torque will be set to 0, vehicle direction fault will be set to 1; To implement the fault, *Vehicle Direction Fault will be inserted into the Camaro Plant Model->Transmission block->TransEstGear*. When commanded shift lever position is in drive, the vehicle will drive in reverse which may cause severe accidents, then the vehicle direction fault will be 1 and vehicle will be shut down. To perform this test, the tester needs to set fault for vehicle direction fault before running the simulation and the fault will be implemented by running fault script. Once the simulation is complete the tester will compare the obtained results with the expected results to determine if the test is passed. The test is considered “passed” when the simulation results match the expected results.		
Test Case Procedure			
Test Initialization:	1) under the Input Conversions->DriverInput_Conversions-> Override LvrPosTrnsShft, set control port to 0. 2) under*Camaro Fault Detection->Input Conversions->TransEstGear*, set control port to 0, override all other signals to normal value. 3) Select the 505 drive cycle from the GUI 4) Set SOC to 90% from the GUI in order to run CD mode as default mode. 5) Run initial fileMain_init.m to initialize the model parameters		
Test Body:	1) Run Fault_Trigger.m to insert the fault, and *Vehicle Direction Fault* (under Camaro Plant Model-> Transmission) will set to 1. 2) Run the model 3) Check the results obtained in the Scope block for each fault		
Test Completion:	1)Record the result 2)Restore the original state of model 3) Run Fault_Clean.m to clean the *Vehicle Direction Fault*		
Test Case Summary			
Expected Results:	***Pass/Fail criteria:*** *1) Vehicle speed=0;* *2) Motor torque output/Engine torque output =0;* • *Under the Signal diagnostic-> Driver signal diagnostic, PRNDL_shift_failed* will be 1, and ->systemDiag->eSystemDiagnostics, eSystemStatus will be 0 and iceSystemStatus will also be 0; • *Under Camaro Plant Model ->Chassis, chas_lin_spd_out, the speed of vehicle will go to 0;* • *Under Camaro Plant Model->IMG->IMG Plant->Electric Machine, mot_trq_out will be 0;*		

Appendix B

B.1 ECMS Algorithm in MATLAB

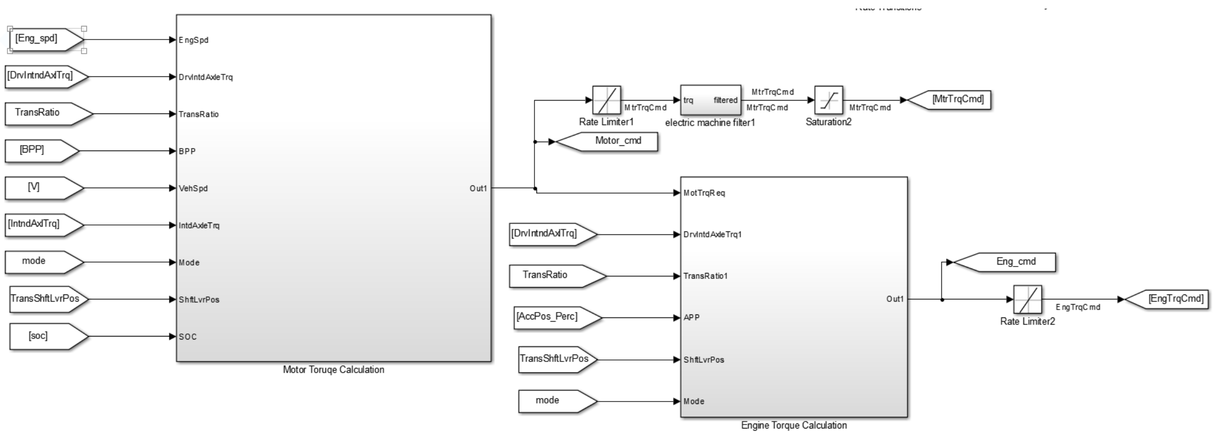
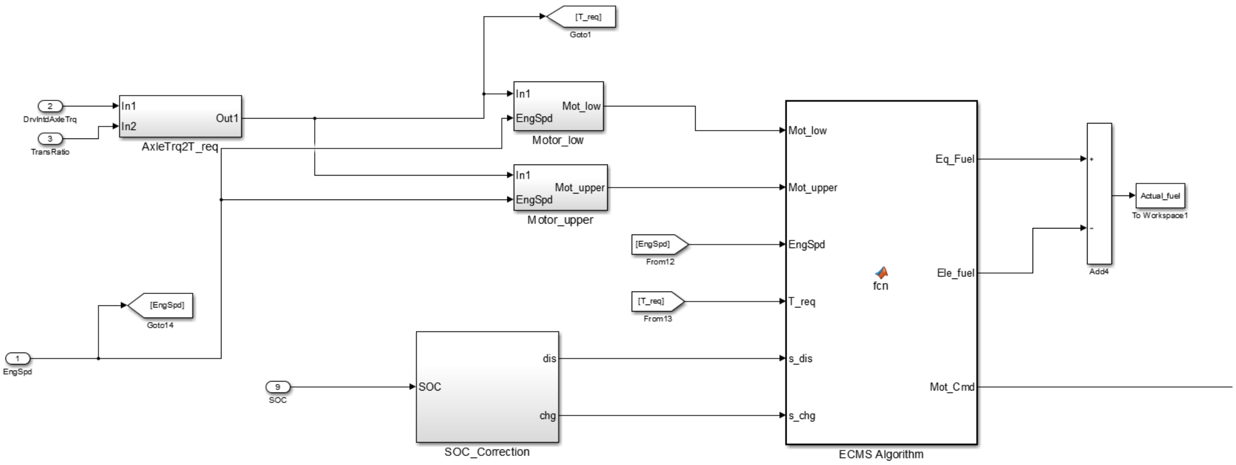


Figure X Engine and Motor torque control based on ECMS



```
function [Eq_Fuel,Ele_fuel,Mot_Cmd] = fcn(Mot_low,Mot_upper,EngSpd,T_req,s_dis,s_chg)

%#codegen

%#codegen

n=0;

i=0;

Equ=0;

Equ_Fuel=0;

Mot_Cmd=0;

delta=0;
```

```
Ele_fuel=0;
Mot_Fuel=0;
Eng_eff=0;
% Eff_eng=zeros(1,20);
Fuel=zeros(1,20);
coder.extrinsic('interp2','linspace');
coder.varsize('Fuel_flow', [1 1024]);
Mot=linspace(Mot_low,Mot_upper,20);
n=length(Mot);
delta=(Mot_upper-Mot_low)/(n-1);
Fuel_flow=zeros(1,20);
for i=1:n
   MotTrq=Mot_low+(i-1)*delta;
   EngTrq=T_req-MotTrq;
% MotTrq=Mot_low;
% EngTrq=T_req-MotTrq;
… % Engine fuel map and motor efficiency map
mot_eff_map = rot90(mot_eff_map,-1);

Eng_FuelRate = coder.nullcopy(zeros(size(EngSpd)));
Eng_FuelRate =interp2(Speed', Tq, FuelRate', EngSpd,EngTrq);
Mot_Trq=abs(MotTrq);
MotSpd=abs(EngSpd);
Heat_value=29401000; % (J/kg)Specific LHV
Eng_eff=EngTrq*EngSpd*(pi/30)/(Eng_FuelRate*Heat_value/1000);
Mot_Eff=coder.nullcopy(zeros(size(EngSpd)));
Mot_Eff =interp2(mot_eff_trq',mot_eff_spd, mot_eff_map',Mot_Trq,EngSpd,'linear')/100;
Mot_Fuel=coder.nullcopy(zeros(size(EngSpd)));
if MotTrq<0
Mot_Fuel=MotTrq*MotSpd*(pi/30)*s_chg*Mot_Eff/Heat_value*1000;
```

```
Fuel(i)=Mot_Fuel;
Equ = coder.nullcopy(zeros(size(EngSpd)));
Equ =Mot_Fuel+Eng_FuelRate;
else
   Mot_Fuel=MotTrq*MotSpd*(pi/30)*s_dis/Mot_Eff/Heat_value*1000;
Fuel(i)=Mot_Fuel;
Equ =Mot_Fuel+Eng_FuelRate;
% Fuel_flow=coder.nullcopy(zeros(1,n));
% Fuel_flow=zeros(1,n);
end
Fuel_flow(i)=Equ;
% end
end
[M,I]=min(Fuel_flow);
Mot_Cmd=Mot_low+(I-1)*delta;
Eq_Fuel=M;
Ele_fuel=Fuel(I);
```

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[29] ECOCAR 3 NON-YEAR-SPECIFIC RULES - REVISION: - JANUARY 27, 2017

Abstract

DEVELOPMENT OF HYBRID SUPERVISORY CONTROLLER AND ENERGY MANAGEMENT STRATEGY FOR P2 PHEV

By

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May 2017

Advisor: Dr. Jerry Ku

Major: Mechanical Engineering

Degree: Master of Science

The EcoCAR3 project is a four-year competition sponsored by General Motors and the U.S. Department of Energy challenging 16 universities teams to reengineer a 2016 Chevrolet Camaro to be a performance plug-in hybrid electric vehicle. A pre-transmission (P2) without clutch parallel architecture was chosen by Wayne State University EcoCAR3 team in Year 3.

The parallel PHEV architecture was modeled by using MATLAB, Simulink and Stateflow for the MIL and SIL environment which was used to test different control strategies. To efficiently distribute the power between engine and electric motor and assess component and system statuses, a hybrid supervisory controller was developed to safely control the interactions between powertrain components.

The thesis details the development of hybrid supervisory controller with emphasis on energy management strategy, a fault diagnosis strategy for safety critical system is also presented in the thesis. A rule-based control strategy is developed to efficiently control hybrid powertrain components in four different operating modes. An optimization based control strategy is then developed to find appropriate torque split between engine and electric motor to reduce the energy consumption in the charge sustaining mode, compared to rule-based control strategy, the optimization based controller effectively reduce the energy consumption on simulated drive cycles.