

**Modeling and Simulation of Plug-in Hybrid Electric Powertrain System
for Different Vehicular Applications**

by

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B.Eng, Beijing University of Technology, 2012

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

Masters of Applied Science

in the Department of Mechanical Engineering

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Supervisory Committee

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Abstract

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The powertrain design and control strategies for three representative hybrid and plug-in hybrid electric vehicles (HEV/PHEVs), a plug-in hybrid passenger car, a plug-in hybrid race car, and a hybrid electric mining truck, have been investigated through the system modeling, simulation and design optimization. First, the pre-transmission gen-set couple Plug-in Series-Parallel Multi-Regime (SPMR) powertrain architecture was selected for PHEV passenger car. Rule-based load following control schemes based on engine optimal control strategy and Equivalent Consumption Minimization Strategy (ECMS) were used for the operation control of the passenger car PHEV powertrain. Secondly, the rear wheel drive (RWD) post-transmission parallel through road powertrain architecture was selected for race car PHEV. A high level supervisory control system and ECMS control strategy have been developed and implemented through the race car's on-board embedded controller using dSPACE MicroAutobox II. In addition, longitudinal adaptive traction control has been added to the vehicle controller for improved drivability and acceleration performance. At last, the feasibility and benefits of powertrain hybridization for heavy-duty mining truck have been investigated, and three hybrid powertrain architectures, series, parallel and diesel-electric, with weight adjusting propulsion system have been modeled and studied. The research explored the common and distinct characteristics of hybrid electric propulsion system technology for different vehicular applications, and formed the foundation for further research and development.

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Chapter 1 Introduction

1.1. Global Energy and Environment Challenges

Our modern society relies on a vast energy supply to fuel everything from transportation to communication, security and health delivery systems. Petroleum fuel has been the main energy source for most countries around the world. The increasing amount of harmful emissions produced by petroleum fuel use becomes the societal concerns, and the driving force for new government policies and technology development plans of automobile manufacturers due to the significant energy consumption in road transportations. According to the US Department of Energy statistics, the worldwide energy consuming in transport is continually growing with a projected growth of 90% between 2000 and 2030. The forecast of world oil consumption by the International Energy Agency (IEA) also suggests a dramatic increase from 82.1 (2004) to 115.4 million barrels of crude oil per day (2030)[1]. This projected increase will cause more severe pollutions in major cities and eventually outpace the supply of petroleum fuels.

Today the major source of CO₂ or greenhouse gas (GHG) and other harmful emissions in the atmosphere are caused by burning fossil fuels. In 2007, the UN Intergovernmental Panel on Climate Change (IPCC) established that human-generated CO₂ is the principal cause of global warming that leads to climate changes with harsh weather conditions in many regions and potentially devastating impacts to some areas of the world [2]. The transportation sector has been identified as one of the top contributors of harmful emissions of GHG, hydro carbons, carbon monoxide, nitrogen oxides etc., due to the fossil fuel (gasoline or diesel) burning internal combustion engine (ICE), contributed almost 27% of total energy consumption in of the world and 33.7% GHG emission in 2012, based on the statistical data from U.S. Energy Information Administration (EIA) [3]. In addition, three quarters of transport greenhouse emissions come from road transport globally [4].

1.2. The Development of Electrified Vehicles

The troublesome environmental and energy supply concerns call for the effective use of electric energy from renewable energy sources and the improvement of energy conversion efficiency in road transportation. The electrification and hybridization of road vehicles will ideally serve these needs. Electrified Vehicles (EVs) could improve energy security by diversifying energy sources and protect environment by improving ICE operation energy efficiency and minimizing tailpipe emissions. According to different power sources for electric propulsion, EVs can be classified into three main categories: battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), and fuel-cell electric vehicles (FCEVs). The combination of BEV and HEV functionality forms the Plug-in Hybrid Electric Vehicle (PHEV). Table 1 shows the characteristics of BEV, HEV and FCEV [5].

Table 1: THE CHARACTERISTICS OF BEV, HEV AND FCEV

Types of EVs →	Battery EVs	Hybrid EVs	Fuel Cell EVs
Propulsion	<ul style="list-style-type: none"> • Electric drives 	<ul style="list-style-type: none"> • Electric drives • ICE 	<ul style="list-style-type: none"> • Electric drives
Energy system	<ul style="list-style-type: none"> • Battery • Ultracapacitor 	<ul style="list-style-type: none"> • ICE • Battery • Ultracapacitor 	<ul style="list-style-type: none"> • Hydrogen fuel cells • Battery • Ultracapacitor
Energy source & Infrastructure	<ul style="list-style-type: none"> • Electric grid charging 	<ul style="list-style-type: none"> • Gasoline stations • Electric grid charging 	<ul style="list-style-type: none"> • Hydrogen • Methanol or gasoline • Ethanol
Characteristics	<ul style="list-style-type: none"> • Zero emission • No petroleum fuel • 100-200 km short range • High initial cost 	<ul style="list-style-type: none"> • Low to very low emission • Long driving range • Need petroleum fuel • Complex 	<ul style="list-style-type: none"> • Zero/ultra-low emission • High energy efficiency • No crude oils • Satisfied driving range • High cost at present
Major issues	<ul style="list-style-type: none"> • Energy management • Charging facilities • Battery cost • Battery life 	<ul style="list-style-type: none"> • Managing multiple energy sources • Depending driving cycle • Battery sizing and management 	<ul style="list-style-type: none"> • Fuel cell cost • Fuel cell life • Fuel production and distribution • Fueling system

From Table 1, it could observe that BEVs, HEV and FCEV are characterized by zero emission or very low emission in pump to wheels. In point of vehicle propulsion, they simply use electric motor drive or electric motor drive combined with internal combustion engine. EVs could be powered mainly by electricity. Consequently, fossil fuel consumption could be greatly reduced. If the electricity comes from renewable

energy like solar power, wind power and so on, EVs can offer a secure, comprehensive, and balanced energy option that is efficient and environmental friendliness. EVs will have the potential to have a great impact on energy and represent one of the most promising pathways to increased energy security and reduced emissions of greenhouse gases and other pollutants.

Up to now three types of EVs were developed worldwide, which are BEVs, HEVs and FCEVs. BEV has attractive benefits such as zero oil consumption, zero tailpipe emissions and better vehicle performance. However, it has some limitations such as high initial cost, short driving range, and long charging time, etc. BEV seems suitable for city drive with short-distance trips [6]. HEVs were developed to overcome the limitations of conventional internal combustion engine (ICE) vehicles and BEVs.

HEVs combine ICE propulsion system with electric propulsion system to obtain better fuel economy than conventional ICE vehicles and longer driving range than BEVs. Plug-in hybrid electric vehicles (PHEVs) have an even longer driving range, because their battery can be recharged externally [7]. HEV could provide better solution for reducing oil consumption and air pollution in transportation area. The design of a HEV is much more complicated and costly especially HEVs with series-parallel powertrain. Still, the success of the first cars on the market (e.g., Toyota Prius) indicates that HEVs constitute a real alternative to ICE vehicles. Moreover, U.S. market trends suggest that PHEVs are becoming a very attractive and promising solution for EVs [8].

FCEVs use fuel cells to generate electricity from hydrogen and air. The electricity is either used to drive the vehicle or stored in an energy-storage device, such as a battery pack or ultra-capacitors. FCVs emit only water vapor and have the potential to be highly efficient. However, at present FCEVs are facing technology challenges such as high cost, limited life cycle of fuel cells, onboard hydrogen storage, hydrogen supply infrastructure, etc. Although prototypes of FCEVs have already been introduced by manufacturers, FCEVs could be a long-term solution.

1.3. HEV and Its Benefits

HEV are vehicles that make use of more than one power supply resources. There are many different possible hybrid powertrain configurations. In general, there are two major types of hybrid powertrain: electric & electric hybrid powertrain and electric & mechanical hybrid powertrain. As far as all kind hybrid powertrain is concerned, electrical energy storage device is essential. The use of energy storage technology could greatly reduce the amount of fuel consumption of vehicle by minimizing engine size and recapturing energy normally lost during braking events. A typical HEV will reduce fuel consumption by about 30% compared with conventional transportations [9]. The most attractive environmental advantage of HEVs, especially plug-in hybrid, is the increased fuel efficiency gained by smaller engines and extended range of pure electric drive. For both automobile manufacturers and customers, it is the most important merit for vehicles consuming less fossil fuel in consideration of oil price and environmental advantage.

Plug-in hybrid electric vehicles (PHEVs) are HEVs which can be charged by the electricity from electric power grid. Fueling vehicles by the electricity from electric power grid allows the transportation energy change to be lower-cost, cleaner and higher renewable. Although BEVs can store electrical energy from electric power grid, it only use battery energy storage which has some weaknesses comparing to conventional petroleum-based fuels such as low specific energy, low energy density and low recharging rate. PHEVs use both battery energy storage and conventional fuel to overcome these weaknesses and to provide additional benefits including higher energy efficiency, lower carbon emissions, lower fueling cost etc.

HEVs provide a pathway for the future of environmental clean vehicle design. Due to the worldwide enforcement on a series of stringent emissions, markets for electric and hybrid vehicles were created as a reflected of the proven success of HEVs that dramatically reduced the amount of toxic emissions released into the earth's and have a potential in eliminating global dependence on fossil fuel. In the meantime, automobile manufacturers have overcome the limitations in cost, reliability and durability of HEVs and found a market demand for them.

1.4. Motivation of System Modeling and Simulation

1.4.1. Foundation for Design Optimization of Hybrid Powertrain

HEVs have advantages in saving fossil fuel and reducing GHG emissions. Meanwhile, they could achieve better drivability and enough driving range comparing with conventional vehicles. The drivability for each hybridization applications can be very different. For instance, drivability for daily driving vehicles focuses more on the smooth transition between each driving mode and provides continuing propulsion torque. Whereas, in auto sport area the drivability is more focused on improve vehicle handling and grip. These benefits come from the diversity of power source from HEV powertrain and the flexibility of control strategies. In general a hybrid powertrain consists of conventional powertrain components, electric driving system and electric energy storage system. Hybrid powertrain design is complex and multi-objective which needs to consider drivability, fuel economy and costs. For PHEV powertrain design, the all-electric range (AER) also has to be considered. One of the most important issues in design of hybrid powertrain is that the vehicle should demonstrate performance (acceleration, maximum cruising speed, etc.) with better fuel economy and less emissions [10-11]. The parameters of hybrid powertrain such as the power capacity of the engine and electric motor, capacity of battery, the transmission gear ratio have a large influence on the vehicle performance, operation energy efficiency, and fuel economy. It is difficult to get overall optimized design of whole hybrid powertrain system by using conventional design methods. Therefore, the parameters of hybrid powertrain need to be determined through modeling, simulation and optimization process.

1.4.2. Foundation for Control Strategy Development of Hybrid Powertrain

Once the selection of powertrain components like engine, electric motor and battery are completed, the next step is to find a hybrid control strategy that determines how power in a powertrain should be distributed as a function of the vehicle parameters such as drivetrain characteristics, battery SOC and driver's demand [12-14] . The main design objective of powertrain control is to achieve optimal energy efficiency. HEVs consume both fuel and electricity. The overall energy efficiency of a hybrid powertrain will be affected by the energy efficiency of both electric driving system and ICE. The control

strategy provides a dynamic control of the vehicle to ensure the best utilization of the onboard energy resources for the given operating conditions. This can be accomplished by controlling the output level of power sources to ensure the highest possible combined efficiency of energy generation and energy exchange with the storage device. So, optimal energy management strategies will be needed to decide how and when energy will be provided by various sources of a hybrid powertrain [15-16]. However, most HEV control strategies were developed on rules of the priority of engine operation energy efficiency. This results in compromising the less significant electric driving system energy efficiency. Optimal control strategies should maximize the ICE operation efficiency, electric driving system energy efficiency and other powertrain components efficiency. Modeling, simulation and optimization will be effective methods for optimal HEV powertrain design and control system development.

1.5. Scope and Organization of the Thesis

This study mainly focus on the analysis of three hybrid powertrain and control system design, which are plug-in electric hybrid passenger car powertrain, plug-in electric hybrid sport car powertrain and hybrid mining truck powertrain. Through modeling, simulation and optimization, the different powertrain design and control strategies were investigated.

The PHEV passenger vehicle case study is based on EcoCAR2 project vehicle, the research carried on with hybrid powertrain design and control system/algorithm study and design. The design objective aims on increasing fuel economy and reducing emission while maintain high safety level and drivability for better driving experience. The powertrain architecture was selected as pre-transmission gen-set couple Plug-in Series-Parallel Multi-Regime (SPMR), which provides a wide range in charge-depletion mode to adjust and fully optimize within daily driving range. As well, the great flexibility of SPMR allowed global optimization approach to fully optimize and highly increase the overall powertrain energy efficiency. Rule-based load following with engine optimal control strategy and Equivalent Consumption Minimization Strategy (ECMS) were designed and modeled for the powertrain system. Control strategy calibration and optimization were realized on simplified power-loss quasi-static Simulink vehicle powertrain plant model. Controller was also built and implemented in a higher fidelity

model based on dSPACE ASM to fulfill model and control system development validation. Vehicle powertrain components were sized and calibrated by simulation in MATLAB/Simulink environment. The case study also involved with MIL, SIL and HIL simulation in order to understand and optimize of vehicle drivability, fuel economy and safety performance.

In this work, a plug-in hybrid electric sport car powertrain based on Formula Hybrid Project was investigated. As a competition project vehicle, the powertrain architecture was selected to rear wheel drive post-transmission parallel through road architecture in aims of high power to weight ratio and reliability. A high level supervisory control system was designed and modeled for the on board embedded controller (dSPACE MicroAutobox II). ECMS control strategy is implemented for endurance competition to minimize fuel consumption in charge-sustaining (CS) mode and enlarge the vehicle range with certain amount of energy. To increase vehicle drivability and acceleration performance, the controller also includes longitudinal adaptive traction control system (ATCS). The ATCS enhance vehicle performance from starting and fast acceleration through low speed area, the adaptive control method also enables vehicle to reach the highest acceleration rates without any pre-knowledge of the tire and road conditions. Simplified power loss mode was built in MATLAB/Simulink for controller validation and control system development, on-board vehicle testing also involves for the propulsion system calibration. The ATCS was tested with a high fidelity model with longitudinal dynamics and scaled components data based on dSPACE ASM to ensure safety and vehicle function.

To fully study different vehicular applications, the research also involves with hybrid electric mining truck. Hybridization in heavy-duty mining truck includes architecture investigation and weight adjusting propulsion system. Three architectures, series, parallel and diesel-electric, were modeled and simulated in MATLAB/Simulink. To overcome the huge fuel consumption causing by engine low speed and high torque operation, the powertrain utilizes wheel hub motors to assist the engine. Regenerative braking from the induction motor largely compensates the energy losses in braking, turning the kinetic energy into electric energy to charge the battery. The control strategy mainly considered

the dramatic vehicle weight changing between loaded and unloaded situation. Weight adjusting propulsion system was designed and modeled to transfer the weight differences into power request and maintains the driver pedal with a constant acceleration and deceleration reaction rate.

This thesis organized as follows. Chapter 1 introduced the background and development of electric vehicles. The motivations and research focus of this thesis were presented. In Chapter 2, the hybrid powertrain architectures and typical hybrid powertrain control and energy management methods were reviewed. Chapter 3 introduced the model based methods and powertrain modeling and simulation tools used in the research work of this thesis. The UVic simulation platform including model in the loop, software in the loop and hardware in the loop was also presented. Chapter 4 explained the powertrain model and the control system design and development for plug-in hybrid electric passenger vehicle EcoCAR2. The vehicle performance and fuel economy were analyzed by the simulations under the proposed powertrain model and control strategies. Chapter 5 presented the vehicle dynamics model and control design for plug-in hybrid electric sport car. The special problems of dynamics control for sport car were explained. In Chapter 6, three typical powertrain systems were taken into comparison and modeled for simulations, the conventional diesel engine configuration, diesel-electric configuration and series hybrid electric powertrain system. The fuel consumptions and GHG emissions of three powertrain configurations were analyzed by simulations. In Chapter 7, the main design considerations on powertrain architectures for different kind hybrid vehicles were concluded. The research contributions of this thesis were summarized. The recommended future research works were proposed.

Chapter 2 Technical Review

2.1. Powertrain Architecture of Hybrid Electric Vehicles

Hybrid powertrain architectures can be classified into two fundamental categories, series and parallel hybrid. In series hybrid architecture the energy sources are coupled together electrically through a DC bus. While in parallel hybrid architecture the energy sources are coupled mechanically through certain mechanical coupling methods such as drive chain or belt. In order to gain the advantages from both series and parallel, many series-parallel hybrid electric powertrain have been developed and tested.

2.1.1. Series Hybrid Electric Powertrain

Series hybrid powertrain architecture is as shown in the Figure 1. It consists of internal combustion engine, generator, energy storage system, converter and electric traction machine.

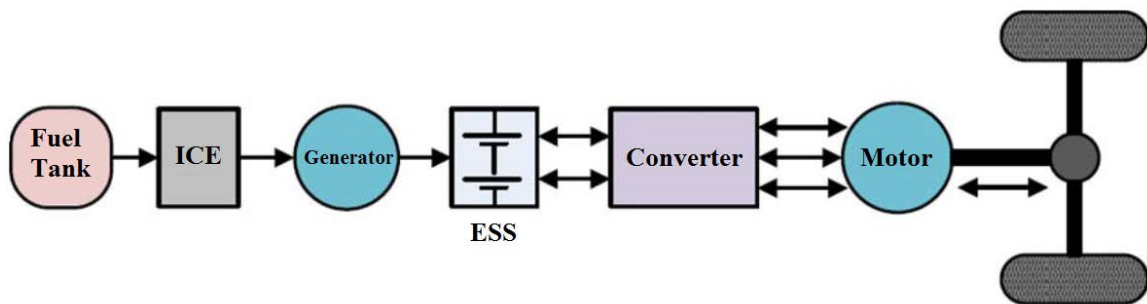


Figure 1: Series Hybrid Powertrain [17]

In this powertrain, all engine output is converted into electric energy and stored into the energy storage device such as a battery or a capacitor. Then the traction motor uses the stored electric energy to propel the vehicle. The advantage of this powertrain architecture is that the engine can be constantly operated in highly efficient areas unrelated to the driving condition since there is no physical connection between the engine and the driveshaft. The disadvantage of a series hybrid powertrain is that it requires a dedicated electricity generator and a dedicated electric traction motor. Furthermore, this system requires larger energy storage device and traction motor to accommodate the whole propulsion power for the overall system. Also, because all propulsion energy must be

delivered through the energy storage device, the charge and discharge losses are relatively large. The series hybrid powertrain is most suitable for city driving circle condition and for heavier vehicle like buses and van.

2.1.2. Parallel Hybrid Electric Powertrain

Parallel powertrain architecture is shown in the Figure 2. Powertrain components combined in a simple structure with an engine, one or more electric motor/generators, an energy storage system and a converter.

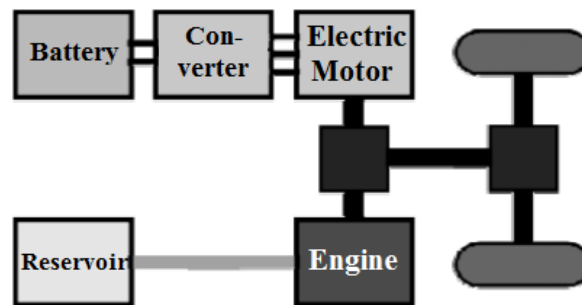


Figure 2: Parallel Hybrid Powertrain [18]

In parallel hybrid powertrain, the drive-shaft can be tuned by the engine just like a conventional vehicle and can also be tuned by the electric motor. The engine and the motor are connected parallel through some form of mechanical coupling and transmission. The parallel operation mechanism of engine and electric motor allows torque blending such that the engine provides most of the constant speed cruising torque and the motor provides accelerating torque. There are many possible way to connect the engine, motor and transmission system, therefore the parallel architecture has many possible configurations which can be sub-categorized into pre-transmission, post-transmission and through-the-road configurations.

2.1.2.1. Pre-transmission Parallel Architecture

Pre-transmission parallel architecture is shown in the Figure 3. In this architecture both the motor and ICE combine their output torques before the transmission. The advantage of this architecture is that the engine could drive the motor like a generator charging the battery, even during stand-still. Besides, as the motor could be driven at a higher speed

than the wheels, it can operate at a lower torque which results in a smaller sized motor. The disadvantage of this architecture is that because the motor is geared to the engine output and input shaft of the transmission, the engine and the motor have to operate at a related speed. This may cause the compromise of whole energy efficiency of the system. Meanwhile, the regenerative braking is disabled or largely reduced in this configuration because of the energy efficiency loss and torque limits from the transmission. This configuration is primarily used in mild (small motor) hybrid vehicles like Honda Insight, Toyota Crown Sedan [19].

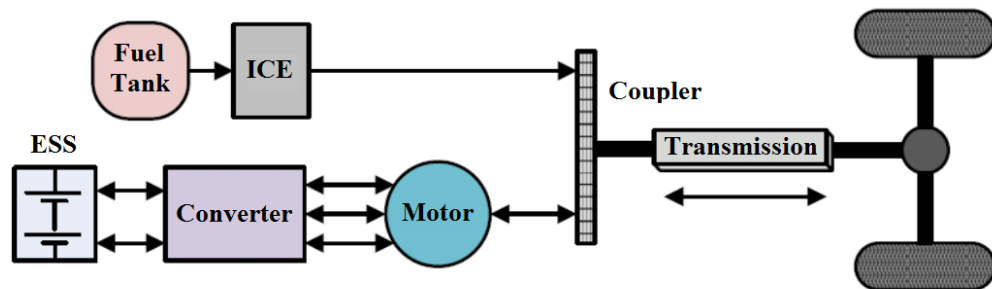


Figure 3: Pre-transmission Parallel Hybrid Architecture [18]

2.1.2.2. Post-transmission Parallel Architecture

The post-transmission parallel architecture that shown in the Figure 4 combines the motor torque, generally through fixed-ratio reduction gearing, with the engine torque after the transmission. However, with the motor coupled to the wheels through its fixed gearing, it must be specified to operate across all vehicle speeds range. The advantage of this architecture is that it is the simplest to implement with very little difference from the conventional powertrain mechanically. Post transmission architectures are typically used in strong (larger motor) hybrid vehicles including light-duty trucks.

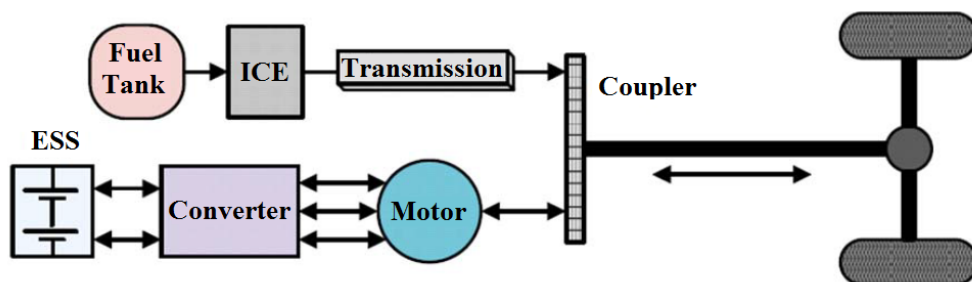


Figure 4: Post-transmission Parallel Hybrid Architecture [18]

2.1.2.3. Through-The-Road (TTR) Architecture

Figure 5 illustrates the through-the-road (TTR) architecture, which is the torque coupled parallel powertrain configuration. In this architecture, the engine and motor operate on front and rear driveshaft respectively. The motor is usually installed as in-wheel design and used to drive rear wheels. There is no dedicated mechanical coupling device for the two power sources. The road acts as a torque coupling means for constraining the front and rear wheels to have the same rotational speed. This configuration offers the possibility of four wheels driving to improve traction performance and converting a conventional vehicle into a hybrid without changing the vehicle's mechanical design. Figure 6 shows how a conventional vehicle is converted into a hybrid vehicle with the TTR architecture. The application examples include the Peugeot 3008 Hybrid, Dodge Durango (prototype) and Jeep Liberty (prototype) [18-19].

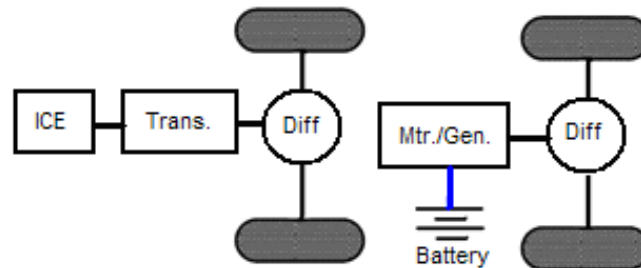


Figure 5: Through-The-Road (TTR) Architecture [18]

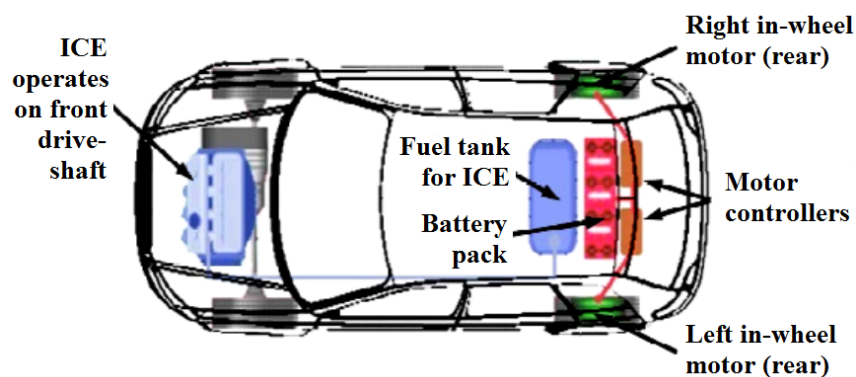


Figure 6: Conventional Vehicle Converted HEV with TTR Architecture [17]

2.1.3. Series-Parallel Hybrid Electric Powertrain

The series-parallel hybrid powertrain may be viewed as a combination of series hybrid and parallel hybrid architecture. In this architecture the engine output is divided into two paths by transmission device. One is a mechanical transmission path directly connected to a driveshaft functioning as the parallel architecture. The other is an electrical transmission path through a generator which is similar to the series architecture. The series-parallel hybrid powertrain is usually called a power-split architecture which requires one ICE and at least two electric machines. The essential feature of the power-split architecture is that it requires a power split device, typically a planetary gear set, which couples the outputs of the ICE and the two electric machines to power the vehicle. Toyota Hybrid System (THS) used in the Prius is a typical power-split architecture as shown in the Figure 7. By controlling the proportion of ICE power in each path, the speed of the ICE can be decoupled from the vehicle speed, thus the power-split hybrid powertrain allows for the operation of electrical CVT.

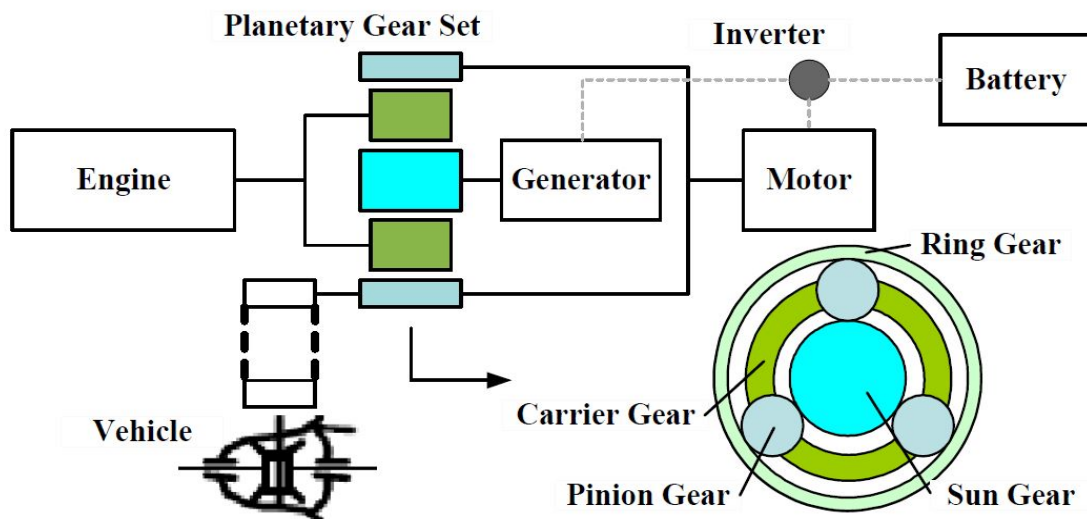


Figure 7: Toyota Hybrid System (THS) Split-Power Architecture [20]

2.1.4. Plug-in Hybrid Electric Vehicle Architecture

A plug-in hybrid electric vehicle (PHEV) was proposed and developed for longer electric driving range. The capacity and energy of the ESS in a PHEV is larger than HEV's and can be recharged by plugging into an electric power source. This feature helps PHEV to achieve very low or zero emission during Charge Depletion mode (CD) or All-Electric

Range (AER) operation mode. In recent years, many automotive industry manufactures started their research and development on PHEV. IEEE-USA Energy Policy Committee defines PHEV as “a hybrid vehicle which contains at least: (1) a battery storage system of 4 kWh or more, used to power the motion of the vehicle; (2) a means of recharging that battery system from an external source of electricity; and (3) an ability to drive at least 16 km (ten miles) in all-electric range, and consume no petrol.” These are distinguished from HEVs that do not use any electricity from the grid [21].

All hybrid powertrains including Series, Parallel, Series-Parallel, and Two-Mode Power Split architectures are compatible to convert into a PHEV [21]. Series configuration has an engine and generator set to recharge the battery, which requires minimum effort to transfer as a PHEV. General Motor made a successful transform converting Chevrolet Volt to PHEV with series powertrain [21]. Because of the mechanical coupling method of the engine and electric drive using in parallel and series-parallel architecture, the electric machine usually sized with lower power capacity and weight. In order to upgrade a parallel or series-parallel hybrid electric powertrain to a PHEV, sizing the electric motor and ESS is necessary. Meanwhile, it is possible for parallel hybrid electric powertrain to power one vehicle's axle by ICE and using electric motor drives the other axle. DaimlerChrysler PHEV Sprinter has this powertrain configuration [21]. Saturn VUE Green Line SUV was the first commercialized PHEV with Two Mode series-parallel hybrid powertrain [21].

2.2. Hybrid Powertrain Control and Energy Management

The efficient operation of an HEV largely depends on the Energy Management System (EMS) which determines the power distribution of each powertrain component along the driver demand. In the powertrain of HEV, the engine, electric motor, generator, transmission, and electric energy storage could be coupled in various mechanisms. The electric motors and batteries could provide more flexibility in engine operation to reach a higher efficient working region. The high level supervisory control system and energy management system of HEV can significantly reduce fuel consumption and emissions without sacrifice any driving experience and comfort. The control strategy and EMS of a hybrid electric powertrain system determines the appropriate power distribution between

the ICE and the ESS. Because the configuration of HEV powertrain is complex and it has multiple operation modes, the control and EMS of a HEV is more complicated comparing to the conventional vehicle.

The idea of hybridization of a propulsion system was originally conceived from the motivation to extend the driving range of electric automobiles [22]. In fact, hybrid powertrain could also provide many advantages such as improving fuel economy, reducing emissions, reducing system cost and improving driving performance. To take fully advantages from hybrid powertrain, the control system design needs to consider following factors [23].

- Optimal Engine Operating Region;
- Engine Dynamics;
- Minimum Engine Speed;
- Battery State of Charge (SOC);
- Relative Power Distribution.

There are many suggested hybrid powertrain control and EMS approaches which could be primarily divided into following two categories: rule-based control and optimization based control [24].

2.2.1. Rule-based Control

A rule-based control strategy consists of sets of predefined (if-then) rules. These rules are initially set based on desirable outputs and expectations without any prior knowledge of the trip, road condition or driver habits. The fast in rules calculation and the adaptive in unknown driving condition make it suitable for real-time control applications. Flowcharts and state diagrams are commonly used to represent the power flow of a given driving schedule. The transition from one mode to another depends on the predefined criteria, such as the power requirements of ICE and electric motor, acceleration or deceleration, vehicle speed, and the ESS SOC. The predefined rules can be obtained from heuristics, human experience, or simulation results. The main goal of rule-based control strategies for HEVs is load following, which moves ICE operation area to its higher efficient region. The difference between the power output of the ICE and the power demands from the driver pedal will be balanced by the ESS and electric driving machines [25]. Some

research works showed that the equivalent consumption minimization strategy (ECMS) can be used in rule-based EMS strategies for fuel savings [26]. Rule-based methods can be divided into two subcategories as deterministic rule-based methods and fuzzy logic rule-based methods. The deterministic rule-based controllers use a set of rules that have been defined and implemented prior to actual operation. The deterministic rule-based controllers are generally implemented via look up tables. Fuzzy logic methods have the decision-making property, which have two following characteristics: 1) robustness, since they are tolerant to imprecise measurements and component variations, and 2) adaptation, since the fuzzy rules can be easily tuned, if necessary [24]. Fuzzy rule-based strategies as a robust control method are suitable for highly nonlinear multi-domain time-varying systems such as HEV propulsion systems.

2.2.2. Optimization-based control

In optimization based control strategies, the optimal operation points such as driving torques, gear ratios and battery charging power are calculated by the minimization of a cost function generally representing the fuel consumption or emissions. System optimization can be implemented by learning and adapting to the condition within a framework of rules or constraints. Several optimization-based control strategies for power management of HEVs have already been proposed. These control strategies could generally be categorized into the following two groups: 1) offline global optimization and 2) real-time optimization [23].

The energy management strategy based on global optimization technique is to get global optimum by minimizing a cost function representing fuel economy and/or emissions along a given driving cycle, as well as considering physical constraints from ICE, ESS and EM. If the optimization is performed over a fixed driving cycle, a global optimum solution can be found. However, the global optimal solution is non-casual, because it relies on a prior knowledge of driving cycle. Unless future driving condition can be predicted during real-time operation, this kind of energy management strategy cannot be implemented directly [27]. Furthermore, global optimization need large amount of time for computation comparing to rule-based EMS. This approach cannot be used directly for real-time energy management. However, it might be a basis of designing rules for online

implementation or comparison for evaluating the quality of other control strategies. There are many global optimization methods such as linear programming, control theory approach, optimal control, dynamic programming (DP), stochastic DP, genetic algorithm and adaptive fuzzy rule-based. DP is a global optimization method for solving complex problems by breaking them into simpler sub-problems [19]. With its global optimization characteristic, Dynamic Programming can be applied in the design phase or be used to improve on line power management strategies. Other optimization methods such as nonlinear convex programming, genetic algorithms, and optimal control theory have all been applied to develop the power-management strategy of HEVs [23].

The energy management strategy based on real-time optimization can be implemented by definition of an instantaneous cost function which depends only upon the system variables at the current time. The instantaneous cost function should include an equivalent fuel consumption to guarantee the self-sustainability of the electrical path. Of course, the solution of such a problem is not globally optimal, but it can be used for real-time implementation. Real-time optimization energy management strategy must be simple enough in order to be implementable with limited computation cost and memory resources. Real-time optimization methods consists of ECMS, decoupling control, robust control, model predictive control (MPC) [3]. In recent years, achieving smooth gear shifting and minimizing excessive driveline vibrations, known as drivability, are included into real-time optimization-based control strategies [24].

2.2.3. Energy Management System for PHEV

PHEVs have large battery pack and can be recharged by power grid, thus they could increase the use of electrical energy and achieve higher overall powertrain energy efficiency. A PHEV's excellent energy economy comes not only from its extended energy storage, but also from its EMS, which determines how energy in a hybrid electric powertrain should be produced and utilized as a function of various vehicle parameters such as power demand, battery's state of charge (SOC), and auxiliary power level. In general, the energy management control problem aims to minimize fuel consumption while keeping the system operating within its constraints without compromising drivability. Due to the complicated operation modes of PHEV, the energy management

strategy for a PEHV becomes even more challenging. A variety of PHEV energy management strategies has been proposed and evaluated in previous studies for different purposes. Among these strategies rule-based strategy, ECMS, DP, Pontryagin's minimum principle (PMP) based strategies are most suitable for the energy management of PHEV [28-33].

Chapter 3 Model-Based Design and Simulation Platform

3.1. Model Based Design Methods

Hybrid electric powertrain is an electromechanical coupling system which requires running in multi-operation modes to achieve safety, highly energy efficient and low or zero emissions. Therefore, the design and optimization of hybrid electric powertrain architecture, energy management system and the control strategy calibration become extremely complex. Model-Based Design (MBD) method provides an efficient design and testing approach for establishing a basic framework for the design process using the development cycle ("V" diagram) as shown in Figure 8. The MBD is different from traditional design methodology. It utilizes models with simulation tools to perform rapid prototyping, software testing, and design verification. In some cases, hardware-in-the-loop (HIL) simulation can be used for testing vehicle dynamics performance and control system diagnostics [34-37]. MBD is becoming an essential way for the rapid building and validation of complex electromechanical systems development in engineering design [38]. MBD involves system analysis, system modeling, control tuning, simulation, automatic code generation, experimental validation, and final control deployment [39].

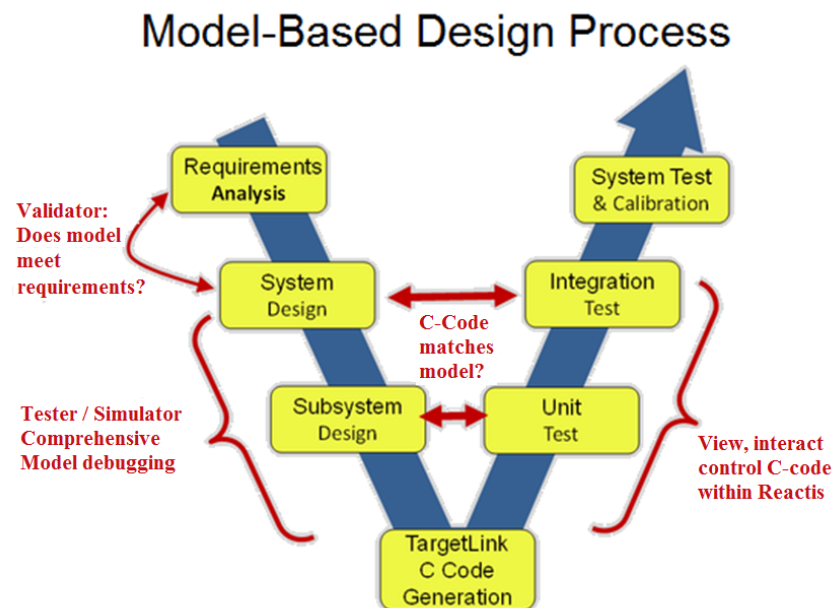


Figure 8: The MBD Process of a Complex System

MBD is a combination of mathematical and visual method to addressing problems associated with complex system design. The process is an interactive design and adjustment process. For instance, if a development obstacle failure is encountered in the V diagram process, the development will go back to previous stage and corresponding steps repeated. Failure at any process of the V will return the current development and design process to the previous related development stage. MBD provides a common and user friendly design environment with general communication, data analysis, and system verification between design and development, which allows engineers to locate and correct errors early in system design. As a result, the time and financial impact of system modification can be minimized.

The MBD method in the system level was implemented in the early stage design and development of UVic hybrid electric vehicles and vehicle control systems as shown in Figure 9. In order to reach the most energy efficient powertrain configuration and to predict the resultant fuel economy over target drive-cycles, the entire design process was divided into eight design steps. The first step is defining powertrain system requirements which have to meet all of the hybrid electric vehicles retrofit project design requirements including vehicle safety, performance and cost. The second step is determining powertrain architecture. By the consideration of maximizing the benefits of various powertrain architectures for the target performance and cost, the powertrain architecture of UVic EcoCAR2 was selected as a 4WD plug-in multiple-regime series-parallel architecture. After the third step model and algorithm development, they will be tested by model in the loop (MIL) simulation. The design prototype is then being adjusted according to the simulation results of powertrain architecture selection and powertrain system integration testing. The components model and its control will be tested by software in the loop (SIL) simulation and the whole powertrain system model and its control strategy will be tested and validated by HIL simulation in the sixth step.

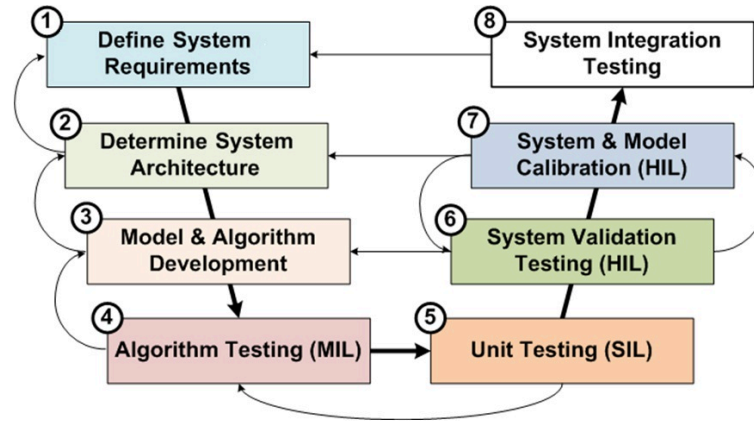


Figure 9: The Model Based Design and Development Process of UVic HEVs

In the model based design and development process, various modeling and simulation tools and simulation testing technologies can be implemented for different design and development phases to meet specific function testing requirement. The typical simulation testing technologies include model in the loop (MIL) simulation, software in the loop (SIL) simulation and hardware in the loop (HIL) simulation. In order to obtain a creditable simulation result, modeling for powertrain system components and control system should be as precise and detailed as possible, which need massive task on theoretical calculation and experimental validation. Through long term development, several simulation tools contain various models for powertrain design was developed by research and development institutions on clean energy vehicles.

3.2. Powertrain Modeling and Simulation Tools

Several simulation tools have been used widely for advanced hybrid electric powertrain research such as ADVISOR, PSAT, PSIM and Autonomie. Each simulation tool has its features and suitable application cases. Depending on the level of details of how each component is modeled, the vehicle model can be classified as steady state, quasi-steady, or dynamic model. For instance, the ADVISOR models can be categorized as a steady state, the PSAT and Autonomie models as quasi-steady and PSIM models as dynamic [40].

The static and quasi-static approach simulates the rigid driving cycle, which assumes the vehicle can follow the driving demand without any speed error. Components models are

built without transient effect using fixed scale torque/consumption energy efficiency map and power loss map. The main advantage of employing a steady state model or quasi-steady model is fast computation, while the disadvantage is inaccuracy for dynamic simulation. Dynamic models are usually used for developing an effective powertrain diagnostics and calibration. The dynamic component models are based on a forward calculation with first-principles description and dynamic equations to unlock the full scale in the degree of freedom.

As for vehicle system model, in general there are two kinds of transient vehicle system models “backward facing models (BFM)” and “forward facing models (FFM)” based on the direction of calculation [40]. The calculation of BFM starts with the tractive effort required at the wheels and “work backward” towards the engine. The calculation of FFM starts with the engine and towards the work in transmitted and reflected torque. BFM are typically much faster than FFM in terms of simulation time. FFM could better represent real world system setup and are preferred where controls development and hardware-in-the-loop will be employed. Detailed vehicle system models typically contain a mix of empirical data, engineering assumptions, and physics based algorithms. Following the two widely used simulation tools ADVISOR and PSAT will be discussed in detail.

3.2.1. ADVISOR

ADVISOR, an abbreviation of ADvanced VehIcle SimulatOR, was developed by the U.S. National Renewable Energy Laboratory (NREL). It was developed for the analysis of performance, fuel economy, and emissions of conventional, electric, hybrid electric, and fuel cell vehicles. ADVISOR program is based on MATLAB/Simulink and is constituted with many subsystem models such as ICE, motor, battery, wheels, driver, etc. It has a set of user friendly user interface of block diagrams which are one to one corresponding to subsystems. Each subsystem has MATLAB file associated with it for defining its parameters initialization and operations which could be changed through m-file or block definition for special modeling requirement. Powertrain component models are open sources and able to replace for particular simulation purpose as long as the inputs and outputs are kept invariable which makes ADVISOR more flexible for different powertrain architectures, components, control strategies, etc [41]. Some subsystems may

be modeled using empirical data obtained from testing. For example, the ICE is modeled using an efficiency map which is obtained from experiment bench tests. The efficiency map defines the static energy losses according to torque and speed map contour. Therefore the engine could not perform beyond these constraints. Besides, ADVISOR allows for the linear scaling of components and for the link with other software packages.

3.2.2. PSAT and Autonomie

The Powertrain System Analysis Toolkit (PSAT) was developed by Argonne National Laboratory and sponsored by the U. S. Department of Energy (DOE) [40]. Developed in MATLAB/Simulink environment, the PSAT is a state-of-the-art flexible simulation package using graphical user interface. Based on the forward-looking model, PSAT allows users to simulate more than 200 predefined configurations, including conventional, pure electric, fuel cell, and hybrid electric architectures (parallel, series, power-split and series-parallel). The large library of component data enables users to simulate light, medium, and heavy-duty vehicles. With quasi-steady models PSAT could predict fuel economy and performance of a vehicle more accurately. Its modeling accuracy has been validated against the Ford P2000 and Toyota Prius. It also has the ability of co-simulation with other environments and running optimization routines. The main drawbacks of PSAT are the incapable to support any component calibration and the large sampling time.

Autonomie is an automotive simulation and analysis tool also developed by Argonne National Laboratory (ANL) and sponsored by the DOE. The MATLAB/Simulink based simulation tool box supports rapid vehicle powertrain modeling and analysis of various powertrain and control systems through the evaluation of vehicle's fuel economy, performance and energy efficiency under various dynamic or transient testing conditions.

3.2.3. Modeling and Simulation with MATLAB/Simulink and SimDriveline

Simulink is one of the most essential components in MATLAB that provides an integrated environment for dynamic system modeling, simulation, and comprehensive analysis. Simulink has very strong visualization functions, which makes it easy to define

a complex system and is able to implement modeling and simulation under continuous sampling, discrete sampling, and continuous-discrete mixed sampling.

SimDriveline is essentially a library of Simulink functions for modeling and simulation of the vehicle powertrain systems. The SimDriveline library includes components such as gears, rotating shafts, clutches, standard transmission templates, and engine and tire models. It is integrated with control design, which allows the user to design controllers and test them in real time with models of powertrain systems. SimDriveline provides a mechanical simulation package that enables engineers to test their engine control units with a software model instead of an expensive drivetrain prototype. Besides, SimDriveline also provides a flexible definition method for inputting information to the standard multi-body simulation package for engineers to quickly and efficiently model the drivetrain system at the desired level of detail. Meanwhile, the SimDriveline also provides a modeling environment that assists in controller development for transmissions and other powertrain components, such as all-wheel-drive center differentials and hybrid electric vehicles.

SimDriveline is a step forward for modeling and control design. Specifically, new solver technology for multi-domain physical modeling is integrated within the Simulink environment to allow accurate and efficient simulation of mechanical systems. The result is that the models produced with SimDriveline allow engineers to perform control design on the entire system in a single environment, and to perform hardware-in-the-loop tests using those same models. The intuitive structure of SimDriveline makes it easy to reuse portions of an existing model in developing new models.

3.3. Model-in-the-Loop Simulation

In Model Based Design method, the target system is usually divided into several units which can be characterized by mathematical dynamic models. After the definition of system requirements, the models of system units and system control strategies should be developed. In general, the mathematical dynamic models are accurate and with high fidelity which could be close enough to represent the dynamic or static behavior of the test system. MIL simulation is a mathematical model based testing technology in the

early phase of system analysis. The objective of MIL simulation is to test unit models and algorithms of the system. It has the potential to enhance convenience and reduce cost of the design and development of HEV powertrain systems [42-45]. In MIL level of system analysis, the numerical and real components of the testing system could interact to give a realistic response for the complete system. Usually the testing data is obtained from real world testing. In this way, rapid system testing can be carried out with both physical testing and computer aided model simulation. In the design and development of UVic hybrid electric vehicles, MIL simulation was adopted to test unit models and develop system control algorithms.

3.4. Software-in-the-Loop Simulation

SIL simulation is a software evaluation testing technology executed in special software environment under simulated input conditions. It is a cost-effective method for evaluating a complex, mission-critical software system before it is used in the real world. Usually the SIL testing only operates depends on CPU's processing speed and is not in real-time execution. The main purpose of the SIL is to prove and verify the algorithms and functions and the basic controller to plant interfaces. With the special requirements, such as components level diagnostics development, the control code requires the software to operate faster than real-time and the simulation speed is largely restricted by both model complexity and CPU processing speed [46-50].

In the design and development of UVic hybrid electric vehicles, SIL simulation was adopted to test control systems, algorithms and signal communications. The layout of SIL simulation is shown in Figure 10. The software code of controllers was incorporated into the MATLAB/Simulink based on Autonomie modeling and simulation tool. Through the compiled C-code and S-Function, the controller's functions can be evaluated by non-real-time simulations.

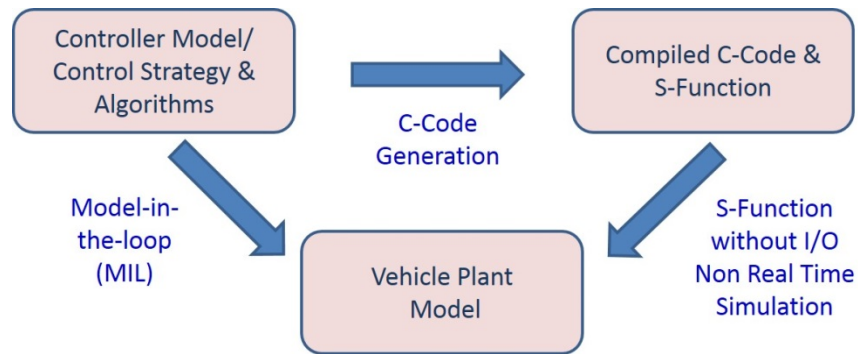


Figure 10: The Layout of SIL Simulation

Our SIL simulation supports the development of generic control algorithms. With a proper signal communication and mapping layout, multiple control algorithms can be compared easily. Meanwhile, our SIL simulation is capable to verify the behaviours of control systems in modeling environment with respect to the production controller.

3.5. Hardware-in-the-Loop Simulation

HIL simulation is an effective testing technology for embedded software in early phase of system design and development. It utilizes real-time processor to simulate the controlled objective connected through I/O boards and CAN boards with PC or Workstation running control strategy and algorithms [51]. HIL simulation has important value for HEV design and development especially for vehicle control system, battery management system and powertrain components subsystem controller [52-53]. In many cases, a physical plant is more expensive than a high fidelity, real-time simulator. Therefore, it is more economical to develop and test new hardware and software by using a HIL simulator than a real plant.

The advantages of HIL simulation are as follows:

- Allow developers to validate new hardware and software automotive solutions in a cost effective way
- Enhance the quality of testing
- Validate controller's ability of the operations in real time

In our design and development work of HEV at UVic HIL simulation was adopted. The layout of HIL simulation is shown in Figure 11.

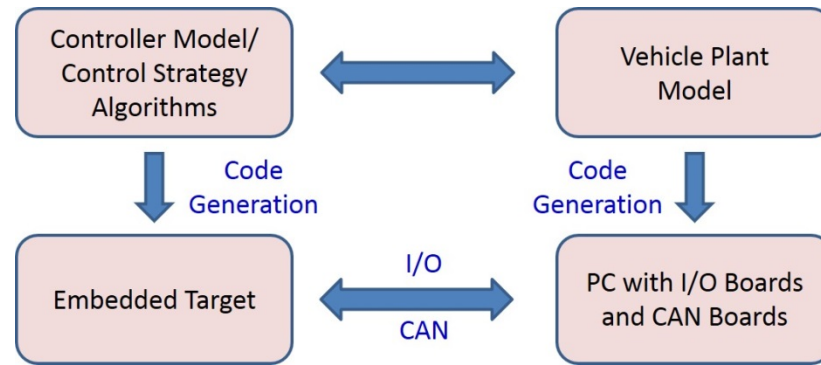


Figure 11: The Layout of HIL Simulation

The HIL simulation platform developed by UVic green vehicle research team was based on dSPACE simulation tool set. The abridged general view of the structure of UVic HIL simulation platform is shown in Figure 12. The vehicle plant model equipped with high fidelity vehicle model – Automotive Simulation Models (ASM) which is an Engine Gasoline model with drivetrain and environment models. The components data was provided by General Motor (GM) and Argonne National Laboratory (ANL). The model libraries and initial files developed by research team makes the simulation much close to the actual vehicle operation situation. The MicroAutoBox II powerful high processing speed controller is used for controller and driver model simulation. It equipped with comprehensive automotive I/O interface which contributed to rapid development process.

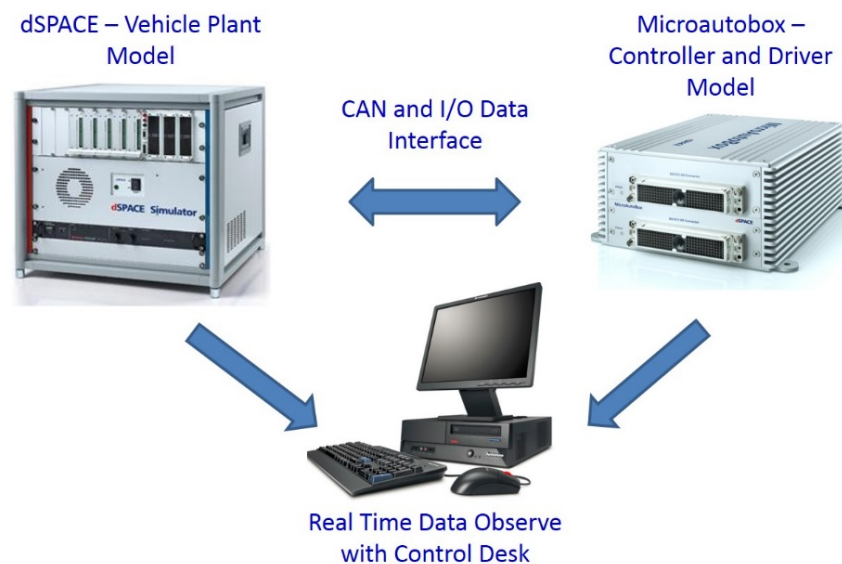


Figure 12: The General Structure of UVic HIL Simulation Platform

Based on the above structure, the UVic HIL simulation platform was developed and applied to different vehicular applications as shown in the Figure 13. The UVic HIL simulation platform is also facilitated with real time interface. The communication and interaction between dSPACE software and hardware is convenient and consistent. This makes vehicle system design, verification and development more rapid, convenient and accurate.



Figure 13: The Overview of UVic HIL Simulation Platform

Chapter 4 Powertrain System Study of Passenger Car PHEV

4.1. Background of EcoCAR 2 Program

The EcoCAR 2 is a three years collegiate vehicle technology engineering competition sponsored by US Department of Energy (DOE) and many automotive industries including General Motors (GM), dSPACE, MathWorks and many other sponsors. The EcoCAR 2 is a program of the Advanced Vehicle Technology Competitions (AVTCs) which is a long term series competition programs for promoting advanced vehicle technology research collaboration between government, industry, and university. The general goal of EcoCAR 2 is to encourage student teams to re-engineer a 2013 Chevrolet Malibu to reduce emissions and environmental impact while retaining performance and consumer appeal. The University of Victoria (UVic) team is the only team in Western Canada, and one of only two Canadian teams competing. UVic plans to build on existing and ongoing hybrid vehicle research, as well as a successful participation in the inaugural EcoCAR competition ending in 2011, by integrating an advanced supervisory control system, cutting-edge electric drive technology, and an advanced Lithium-Ion battery into a plug-in hybrid electric vehicle (PHEV) design.



Figure 14: UVic EcoCAR 2 in the Autocross Event at Final Competition

The UVic EcoCAR 2 started as a 2013 Chevrolet Malibu Eco mild-hybrid, which was transformed to a PHEV by replacing the powertrain system with a 4WD series-parallel multiple-regime plug-in hybrid electric powertrain. Table 2 presents the vehicle technical

specifications of the UVic EcoCAR2. This powertrain includes a large BAS electric machine attached to the 2.4L E85 ICE at front and added rear electric drive using another high power traction permanent magnet synchronous planar motor to gain better performance, fuel economy and powertrain energy efficiency. The vehicle passed the test by multiple control situations for the evaluation of fuel consumption, well to wheel energy efficiency, emissions criteria, total energy consumption, accelerating and braking distance, dynamic handling, ride comfort, Noise Vibration and Harshness (NVH) characteristics and static consumer acceptability. The Figure 14 shows the UVic EcoCAR 2 competing in its Autocross event at Year 3 Competition.

Table 2: THE VEHICLE TECHNICAL SPECIFICATIONS OF UVIC ECOCAR2

Specifications	Values
0-60 Acceleration	8.5 s
50-70 Acceleration	3.6 s
60-0 Braking	43.5 m
Mass	2078 kg
Peak Power	454 hp
Charge Depleting Range	63 km
Charge Sustaining Fuel Economy	8.24 Lge/100km
UF-Weighted Fuel Economy	4.93 Lge/100km
Emissions	204 g/km
Range	346 km
Ground Clearance	147 mm

The author joined the UVic Hybrid Powertrain Research Group since the end of 2012 and conducted research works on modeling and simulation for EcoCAR2 powertrain architecture and control system design and evaluation.

4.2. Design Objectives and Approaches

The main purpose of this work is to investigate and discover the key features of the daily drive purpose passenger hybrid electric vehicle. In developing a generic advanced passenger PHEV, the main design objective is the low life-cycle costs while satisfying

reasonable performance, drivability, safety, and utility requirements. The upcoming 2016 Corporate Average Fuel Economy (CAFE) law towards manufacturers requires the average fuel economy for cars must higher than 34.1 mpg, up 35 percent from the current 25.3 mpg, which is a huge jumping compare to previous years requirement. The changing in automotive industry requirement and standard drives the design objective to concern more in fuel efficiency, investment cost and longevity.

This study focused on the design and optimization of high fuel efficiency for the passenger vehicle. Powertrain architecture selection process, and vehicle powertrain performance modeling and simulations using different measures, vehicle calibrations, and optimizations are presented.

Experiment design is becoming an essential tool for the rapid building and validation of mechanistic models in engineering design. The high system complexity and high risk danger ramifications of testing the vehicle control system on-road result in necessary automated system testing procedures being integrated into the system validation process. In this study, Model-Based Design (MBD) process was utilized to develop the control systems and vehicle architecture for the SPMR-PHEV application.

The control system has been developed using a systematic approach, with stages of high-level and model-based design preceding stages of incremental testing and integration with the physical vehicle systems. A high-level view of the development method employed is outlined in the modified V diagram shown in Figure 9.

4.3. Vehicle Powertrain Configuration and Key Parameters

The SPMR-PHEV powertrain architecture was designed and retrofitted to a market-ready passenger car, UVic EcoCAR 2. The main design goals include reducing overall greenhouse gas emissions (GHG), increasing fuel efficiency and improving vehicle driveability. The powertrain consists of a 103kW PMSM rear traction motor/generator (RTM), a 2.4L GM EcoTec LE9 engine running with E85 fuel, coupled with a 105kW belt alternator starter (BAS) motor/generator acting as a gen-set, and a 16.2 kWh A123 Li-ion battery pack serving as onboard energy storage system (ESS) with plug-in

charging capability. The layout of EcoCAR2 powertrain was shown in Figure 15 and the powertrain architecture and energy pathways were illustrated in Figure 16.

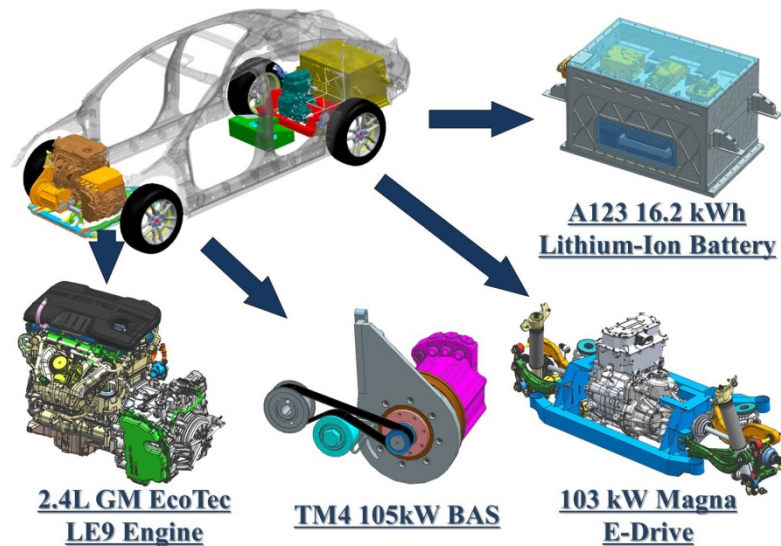


Figure 15: The Layout of EcoCAR2 Powertrain

The series-parallel powertrain architecture supports multiple regimes of operation including electric drive only (EV) mode, as well as various series, parallel and series-parallel hybrid operations. Traction power available through front wheel drive (FWD), rear wheel drive (RWD) and all wheels drive (AWD). Engine start/stop function and creep torque were integrated to achieve further fuel saving and better vehicle control for safety. The multi-regimes architecture also provide a platform in research area on advanced hybrid controls to optimize the operation mode towards certain driving patterns aims to reduce energy consumptions, improve vehicle drivability and provide various utilities.

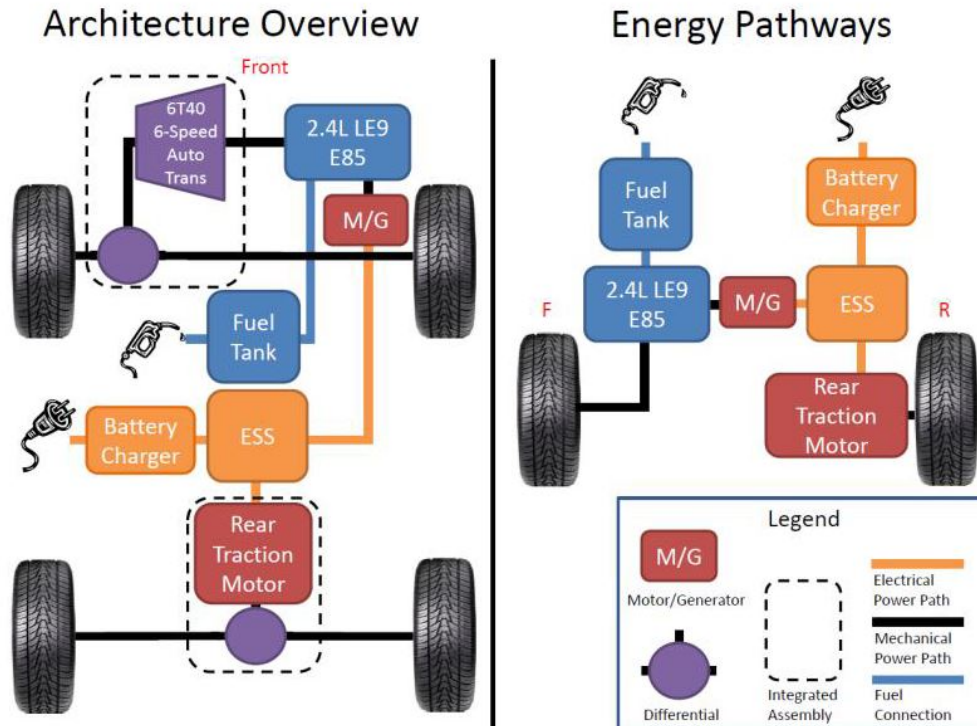


Figure 16: Diagram of SPMR-PHEV Architecture

This powertrain configuration provides many substantial improvements over the production 2013 Malibu. These are accomplished by virtue of the tremendous operational flexibility the architecture is capable of providing. A key feature of the UVic PHEV architecture is the employment of a multi-regime control scheme. Unlocking the full optimization potential of the vehicle architecture requires the flexibility to switch between various operating modes when it is ideal to do so.

4.4. Powertrain Modeling

4.4.1. Powertrain Components Modeling

The simplified system power loss meta-model was built in order to study the effective of the multi-regime architecture and the control strategies effects towards vehicle fuel economy. The quasi-static models [54] do not consider transient response of vehicle components and use static energy efficiency maps and fuel consumption maps for the engine and the motor. The forward and backward-looking model also includes a driver model: a PID controller that compares the vehicle speed with the desired vehicle speed

(driving cycle) and generates acceleration and brake commands. The low level of fidelity makes the MIL platform unsuitable for development of lower level component interface algorithms and drive tuning algorithms. Since powertrain components are modeled simply as power loss tables, detailed component transient effects are not captured. Additionally, component ECU behaviour is not simulated, so supervisory controller inputs directly result in output response from components, accounting for any physical component performance limitations. Model detail is kept simple in the MIL model to speed up computation. Manufacturer-provided data was used to construct quasi-static models built on component power loss lookup tables. The quick run-time and relative simplicity make it a good platform for developing energy management strategies in a manageably isolated, yet relevant simulation framework.

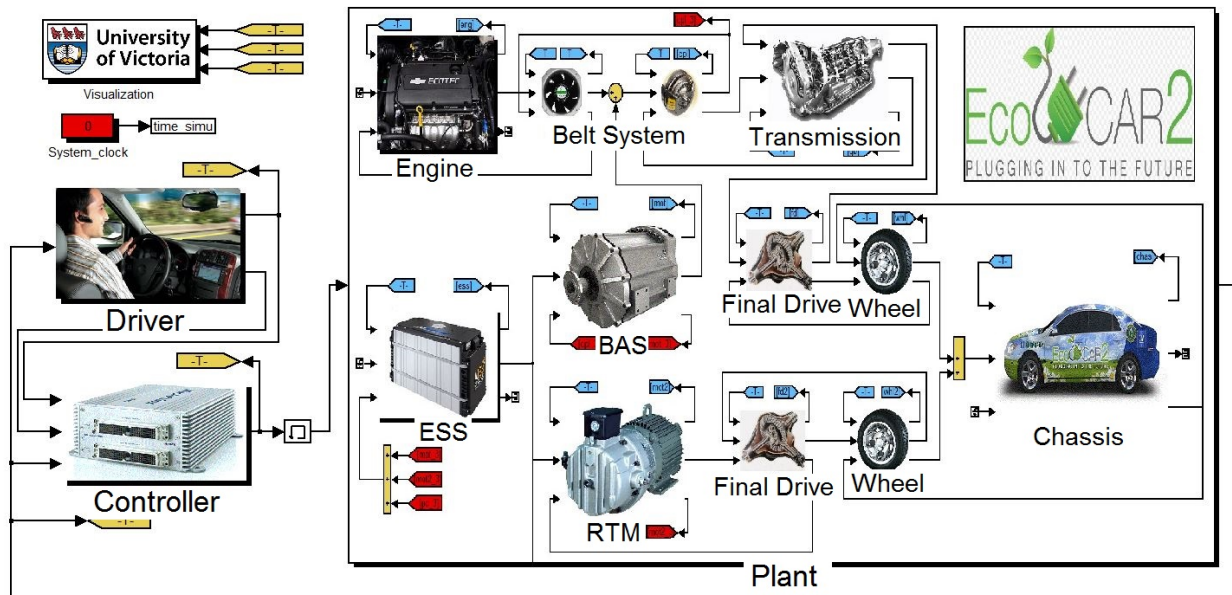


Figure 17: Simulink Based Simplified System Power Loss Model

The proposed quasi-static SPMR-PHEV powertrain model can be used for the characterization of basic vehicle performance and dynamics. The component models of the hybrid powertrain including models of the E85 engine, belt-alternator starter (BAS) motor/generator, belt system, energy storage system (ESS), rear traction motor, transmission, and vehicle longitudinal dynamics. The powertrain performance model used backward calculation from wheel reaction back to each powertrain component. Component torque loss, energy efficiency and operation map are incorporated using

predefined look-up table. Detailed components data are obtained from steady-state experimental testing to predict vehicle fuel economy and powertrain energy efficiency.

4.4.2. Driving Schedule

Vehicle performance simulations of the multiple-regime series-parallel passenger vehicle model were carried out under consistent conditions and time-dependent operational profile for fuel consumption analysis, component sizing selection, and calibration of control methods. Three typical industrial standard drive cycles were selected including US06, UDDS and HWFET, to serve the purpose of testing powertrain control system and evaluate vehicle fuel consumption.

4.4.2.1. US06 Drive Cycle

A standard daily driving cycle, US06 cycle as shown in Figure 18, were selected for vehicle performance and fuel economy simulation. The vehicle target speed was directly obtained from real world driving data from US EPA. The US06 Supplemental Federal Test Procedure (SFTP) was generated to represent of high power aggressive and high speed driving behaviour with frequent speed variations. The US06 lasts 10 minutes with an average of 48 mph in driving speed, covered of 8 miles in distance and reached top speed at 80 mph.

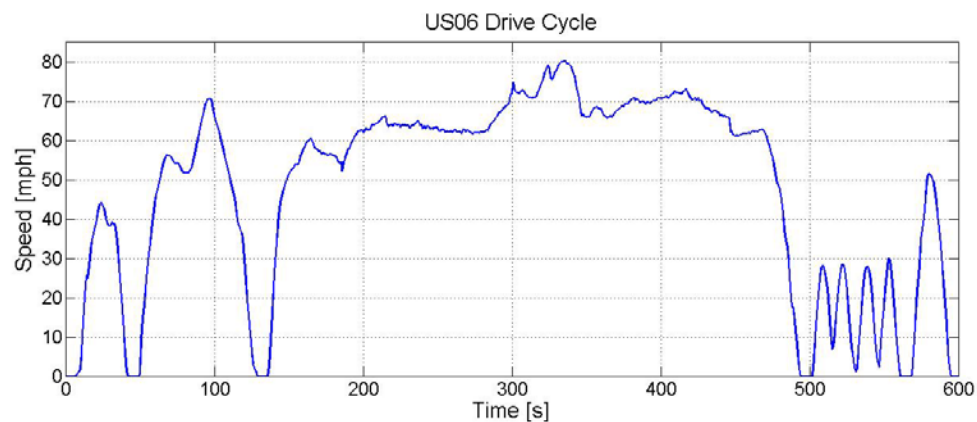


Figure 18: US06 Driving Cycle

4.4.2.2. UDDS Drive Cycle

The Urban Dynamometer Driving Schedule (UDDS) is a representative driving condition of city road. It is a mandate dynamometer test for vehicle tailpipe emissions. The UDDS simulates a frequent stop urban route situation in 7.5 mile distance. Vehicle reaches top speed at 56.7 mph and 19.6 mph in average speed. The UDDS drive cycle is shown as Figure 19.

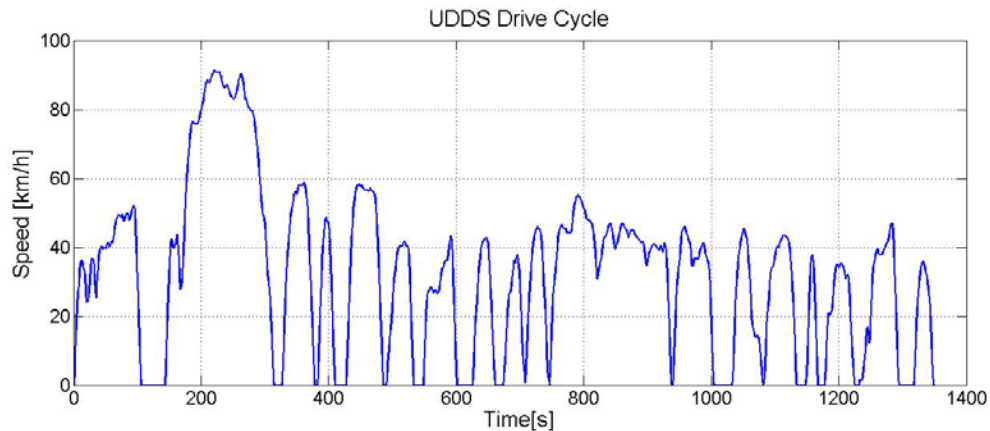


Figure 19: UDDS Driving Cycle

4.4.2.3. HWFET Drive Cycle

The Highway Fuel Economy Test (HWFET) drive cycle that shown in Figure 20, is a dynamometer testing schedule developed by the US EPA for high speed application fuel economy tests of light duty vehicles. The cycle length is 765 seconds, with 10.25 mile in distance and 48.3 mph of average speed.

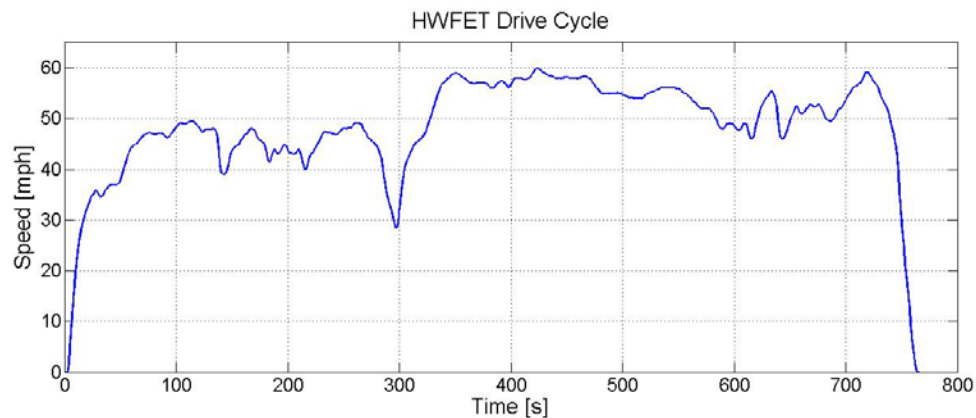


Figure 20: HWFET Drive Cycle

4.4.3. Vehicle Dynamics Modeling

The vehicle dynamics model is used to capture the interactions between the vehicle and the chassis glider elements, which refer to vehicle dynamic parameters, including vehicle mass, final drive ratio, wheel rolling resistance, wheel radius, drag coefficient, and height of the center of gravity. Vehicle road load generally consists of four major forces: rolling resistant force (F_f), aerodynamic resistant force (F_w), acceleration force (F_j) and incline force (F_i). The driving forces can be calculated using either the curve fitting (2), or the empirical (3). The solutions based on the two functions sets are virtually identical.

$$\sum F = F_f + F_w + F_i + F_j \quad (1)$$

$$\sum F = F_0 + F_1v + F_2v^2 + F_j \quad (2)$$

$$\sum F = mg \sin(\alpha) + mgC_r + \frac{1}{2} \rho C_d A_f v^2 + ma \quad (3)$$

Where α is the grade, m is the vehicle inertial mass (kg), C_r is the rolling resistance, ρ is the density of air ($1.2\text{kg}/\text{m}^3$), C_d is the drag coefficient, A_f is the front area, v is the vehicle speed (m/s) and 'a' is the vehicle acceleration (m/s^2).

4.4.4. Internal Combustion Engine Modeling

The engine model is based on the GM LE9 E85 2.4L DOHC SIDI EcoTec flexible fuel engine. Several characteristics such as engine speed limit, maximum and minimum torque, fuel consumption rate and emissions rate are modeled using lookup tables. The engine speed and torque are inputs to the emission model, which are used to calculate the fuel consumption rate and emissions rate, respectively. Figure 21 shows the engine operating curve with fuel consumptions (g/s).

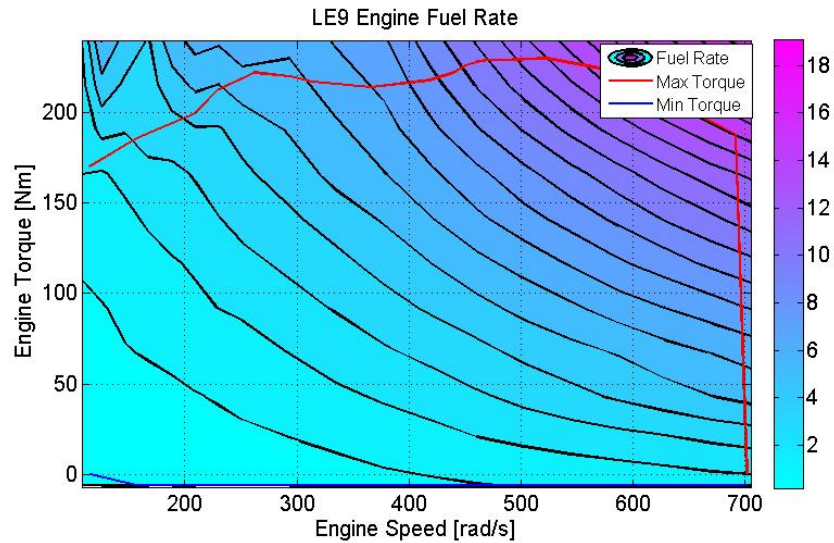


Figure 21: Engine Operation Curve with Fuel Consumption Map

4.4.5. Motor/Generators (MGs) Modeling

Two electric machines were modeled, 103kW Magna e-Drive (RTM) and 80kW TM4 Motive (BAS Motor). Similar to the engine, component losses and electrical energy usage are calculated under limitations determined by component parameter scaling and through energy efficiency calculations based on both speed and torque demands provided by the vehicle controller. Since the BAS motor is coupled directly to the engine's crankshaft, the speeds of the BAS motor and engine are always identical. Figure 22 and Figure 23 depict MG operating curve and energy efficiency of the RTM and BAS Motor, respectively.

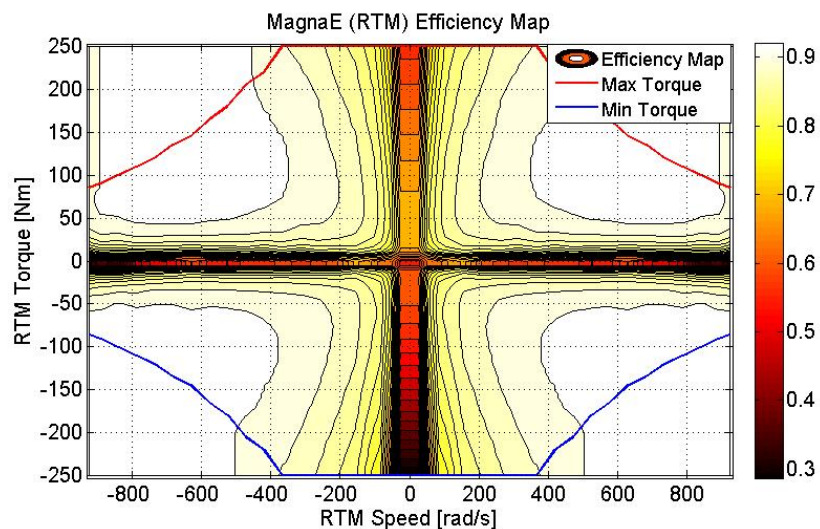


Figure 22: MagnaE (RTM) Operating Curve with Efficiency Map

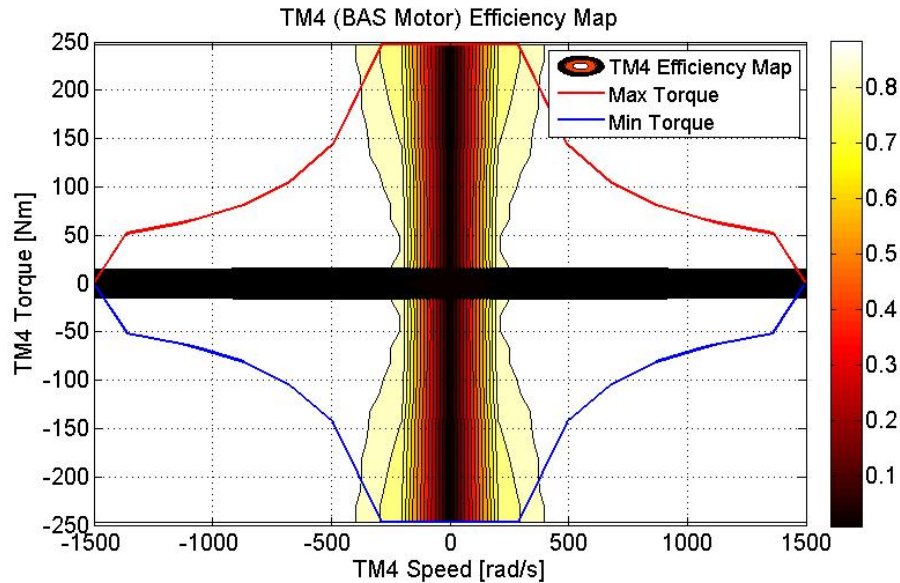


Figure 23: TM4 (BAS) Operating Curve with Efficiency Map

4.4.6. Energy Storage System Modeling

In this ESS model, a 292 V and 14.8 kWh batteries pack with 6-modules of 15-series-3-parallel A123 lithium-ion cells is selected to observe electric consumption. The ESS model consists of a number of functions that calculate a variety of states of charge (SOC) as well as battery voltage and internal resistance.

The internal resistance model assumes the battery as an equivalent resistive circuit in series with a voltage source. The model fits in rapid development and gives reasonable results, but due to absence of capacitor, the voltage is prone to be very sensitive and can vary drastically. While charging, the amount of charge stored is limited by a maximum battery voltage and is influenced by the coulombic efficiency. Battery is considered as a voltage source with varying but known resistance values, and the other connected components, for instance motor and generator, are supposed as power sinks. These sinks dictate the limitation in amount of power drawn from battery by the maximum power they can handle.

As shown in (4), the energy consumed by the MGs is calculated at each time step, and is added to the available energy values obtained in the previous time step. The battery state of charge (SOC) is calculated using (5), dividing the current energy value by the

maximum energy capacity of the battery. The initial SOC of the battery was specified at the start of the simulation.

$$\sum E = \int P_{MGs} dt \quad (4)$$

$$\sum SOC = SOC_{init} + \int \frac{I_{bat}}{3600 \times C_{bat}} dt \quad (5)$$

Where, E is the energy consumed or generated from ESS, P_{MGs} is the power consumed by electric machines, SOC_{init} is the initial state of charge of the battery, I_{bat} is the current from battery pack and C_{bat} is the battery capacity.

4.5. Model Validation

4.5.1. Model Validation through Simulation Results Comparison

In order to identify the performance and the fuel economy improvements under the rule-based control strategy, the SimDriveline based multiple-regime series-parallel PHEV model was validated and evaluated by comparing its simulation results with Prius Simulink model and two previously tested HEV models in Autonomie, the production Malibu model and Prius model as shown in the Table 3. Due to the limitations of modeling tool, the BAS with RWD multi-regime powertrain architecture studied in this research cannot be modeled in Autonomie. Therefore, a Prius model built in same method and control strategy under Simulink environment is also provided.

Table 3: POWERTRAIN MODEL TESTS

	Power split (Prius)	BAS (GM Malibu 2013)	BAS & RWD (UVic EcoCAR2)
AUTONOMIE Model (Baseline Rule Based Control)	✓	✓	
Simulink/SimDriveline (Optimal tuned Rule Based Control)	✓		✓

Autonomie is an automotive simulation and analysis program developed by US DOE's Argonne National Laboratory (ANL). The program supports quick modeling and analysis

of various powertrain and propulsion systems through the evaluation of vehicle's fuel economy under various dynamic or transient testing conditions.

The power-split HEV Prius model in Autonomie has been tested and continuously improved using real world data over the past few years, while the mild hybrid electric powertrain of the production 2013 Malibu Eco was built in UVic research group work by Jackie Dong. This model is based on the Autonomie template of a parallel pre-transmission automatic HEV 2WD configuration, where the energy management strategy is adopted from Autonomie powertrain component systems controller library and serves as a baseline control strategy. Figure 24 shows the production Malibu model powertrain layout.

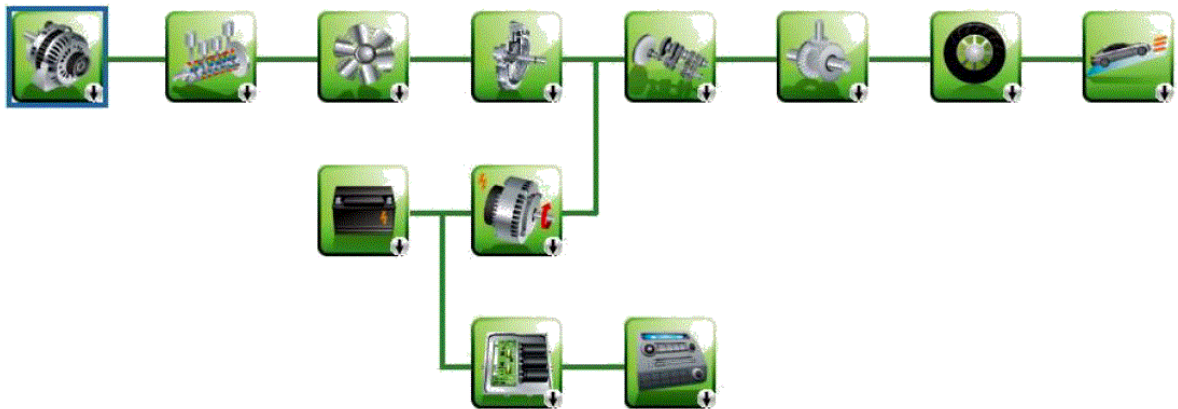


Figure 24: Production Malibu Powertrain Layout

According to the simulation results of vehicle performance and fuel economy shown in Table 10 and Table 11, the Simulink model of vehicle performance of Prius (Acceleration time and Top speed) is close to the Autonomie model. The Simulink model of fuel economy of Prius shows a slight improvement due to the different energy management strategies from the system rule based controller library. Under eight times of US06 city drive cycle, the simulation results for both Prius model were generally close. Therefore, the comparison between the Simulink/SimDriveline model of BAS & RWD and the Autonomie model of BAS will be fair.

4.5.2. Power Loss Model Validation

The power loss model validation was done by a comparison simulation output with a higher fidelity model - dSPACE ASM based UVic EcoCAR 2 Model. The model includes detailed very high fidelity ICE and drivetrain dynamics model calibrated with industrial level and components data provided mostly by dSPACE and GM. UVic green vehicle research group also self built the electric path of the powertrain system with detailed sub-system controller. The modeling method and data were collected from either physical bench tests or from industrial production information. Most of the powertrain component models are high fidelity level that allow for vehicle propulsion system and control system validation and diagnostics testing. The accurate in ICE physical model and detailed ICE, ESS and RTM soft-ECU model are able to carry the signal communication validation. The high fidelity in physical and sub-system controller enabled the development of vehicle global diagnostic algorithms and higher level control strategies.

The quasi-static simplified power loss model validation is done by comparison simulation with the relative outputs from high fidelity dSPACE UVic EcoCAR2 model using industrial standard drive cycle. In the validation process, two types of model are implemented an identical control strategy and EMS while the high fidelity model includes more global diagnostics block and drivability constrains. Relevant controller commands and expected energy consumptions and the testing results are listed as following.

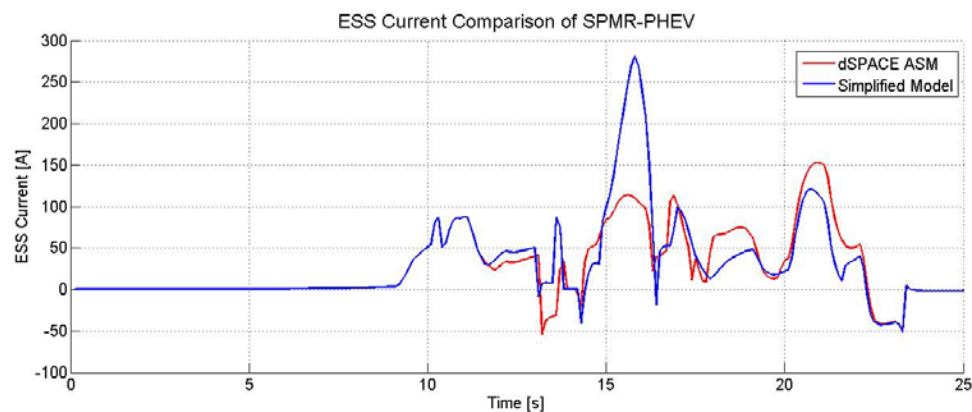


Figure 25: ESS Current Simulation Results Comparison

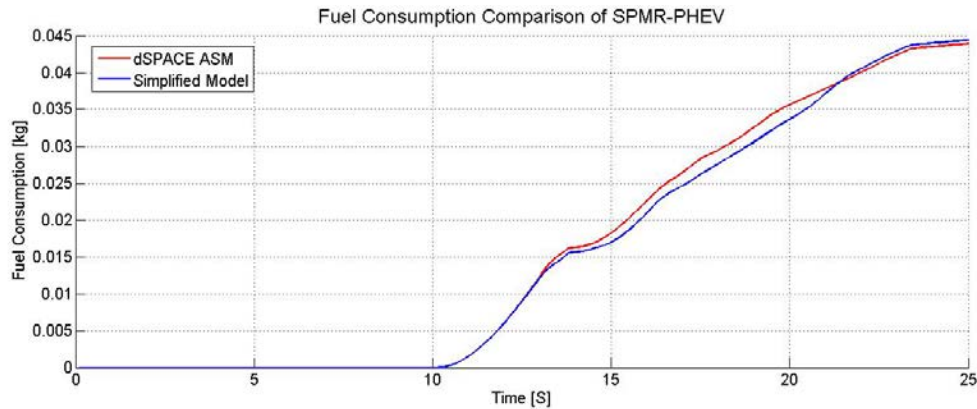


Figure 26: Fuel Consumption Simulation Results Comparison

The simulation results of the ESS and fuel consumption shown in Figure 25 and Figure 26 indicate that the simplified model has a relatively close overall performance as the higher fidelity model. Due to the lack of sub-components ECU and the dynamic reacts, the response are difference during frequent vehicle transient in starting where the dynamic effects of the model cannot be neglected in the simulation results. However, the energy consumption and vehicle ESS performance behaviour is relatively similar for the simplified model and dSPACE ASM.

4.6. Vehicle Powertrain Control strategies

Control strategies and algorithms used in hybrid electric powertrain controller can affect extensively in fuel consumption. Due to the complexity of the UVic EcoCAR2 Series-Parallel Multiple-Regime architecture and the various electrical and mechanical power paths available between the ICE, BAS, ESS and RTM, there are many options available in developing a suitable control strategy. Driving with fully charged ESS or at low-speed scenario causes the supervisory controller to favor the RTM, as it provides sufficient tractive power at far greater energy efficiency than the ICE under certain conditions. To maintain drivability while not sacrifice much in performance, an RTM/ICE power blend is implemented based on available versus commanded torque and the energy efficiency trade-offs between components. A limitation to the designed hybrid electric architecture is that the BAS motor cannot provide traction while the engine is inactive because of the belt coupling system in pre-transmission configuration. Therefore, all-electric driving

mode using only the RTM. Once the engine is enabled, the vehicle operates in AWD or FWD.

To develop a proper strategy for vehicle supervisory controller requires control algorithm optimizations. In this work, two control strategies were modeled in Simulink and taken into comparison - rule-based load following strategy and equivalent consumption minimization strategy (ECMS).

4.6.1. Rule-Based Control Strategy

The rule-based control strategy is a load following strategy [55-56]. It was designed for SPMR-PHEV architecture and combined a local optimization method to calibrate on engine operational area. The flexibility of the powertrain architecture which reflected by multiple possibilities in electrical and mechanical power paths needs a well-defined state-of-the-art control strategy for the control system. A specific deterministic rule-based load-leveling energy management system was built in MATLAB/Simulink environment for this certain vehicle plant model.

In this strategy, at the fully charged ESS condition, the vehicle will run as a pure electric vehicle except the occasionally exceeding in power demand. In the CD range, ICE and BAS motor only provide alternator power to adjust load request from driver. As the battery state of charge (SOC) drops to a certain level, the vehicle will operate in charge sustain (CS) mode as a normal hybrid electric vehicle with the engine meeting most of the loads to obtain a constant SOC level. The engine operation points were controlled and adjusted by BAS motor and the belt system. The BAS motor controls ICE starting and operating points as close as possible to the maximum energy efficiency operation area as shown in Figure 27. Engine fuel consumption and energy efficiency data map was collected from real world engine laboratory tests. Meanwhile, the RTM meets the rest of the power requirements at each loading scenarios. This rule-based strategy is suitable and flexible as it does not need pre-knowledge of a driving cycle.

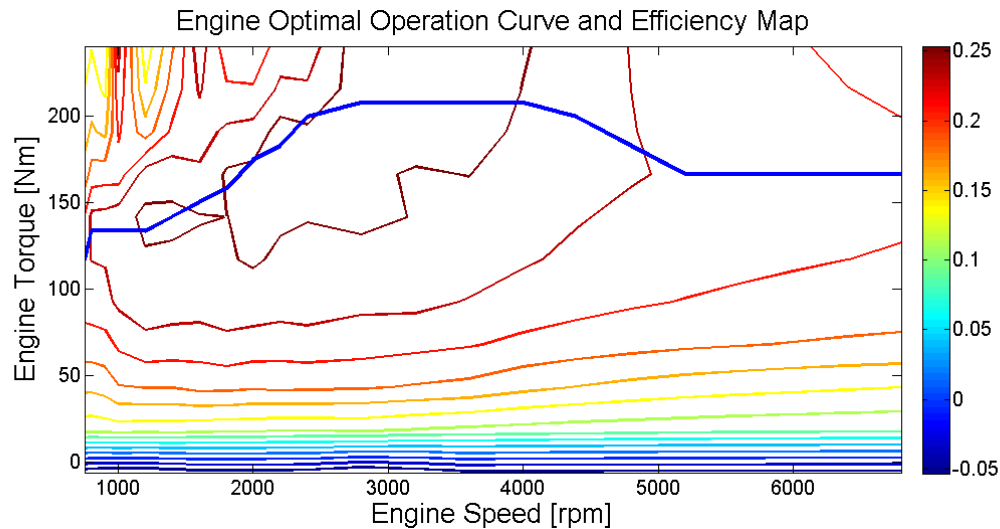


Figure 27: Engine Optimal Operation Curve with Efficiency Map

A pre-defined variable for the power load threshold was used to control the engine assist frequency and the CD range will be adjusted by the frequency of the engine on/off. When the battery reaches the low SOC level, the vehicle operates as mild HEV with regenerative braking and BAS power assist. State flow logic shown in Figure 28 is generated to control the driving mode according to load request and driver demand. In this application, three states were used, EV mode, Series-Parallel mode and Parallel mode, for most driving conditions.

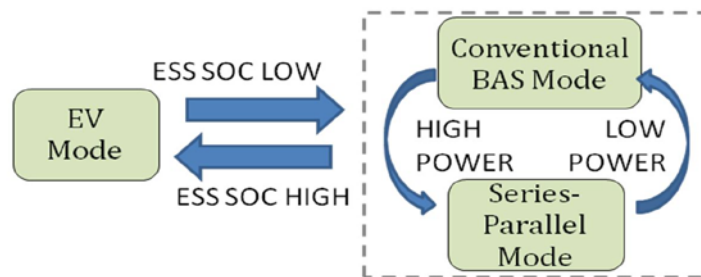


Figure 28: The State Flow Logic of Mode Transitions

The rule-based controller operates on a set of rules that have been defined and implemented prior to actual operation. The state-machine-based control logic flow is shown in the Figure 28. The vehicle modes of operation were subtracted as different states, such as power state, saving state and performances state. In the state flow

controller, vehicle inputs and feedbacks formed certain of states and situations which determined transitions between each state and sending out different power distribution actions. An example of modes selection rule is listed as below.

If *VEHICLE SPEED is higher than 10 m/s;*
 SOC is higher than 15%;
 “no” is equal to ev_mode_only;
 “no” is equal to system_epo;
 Then *“yes” is assigned to hybrid_enable;*
 Find ideal_mode_value;
 End

4.6.2. Equivalent Consumption Minimization Strategy (ECMS)

Compare to the component level local minimum optimization, the Equivalent Consumption Minimization Strategy (ECMS) presents to be more robust and efficient in fuel consumption minimization while in CS mode. As the fuel consumption is the only objective, ECMS is considered as a sub-global optimization method, where two power sources will get combined and generated an equivalent weight for optimization to reach a minimum fuel consumption point at each time. The control problem for PHEV follows the same concepts as hybrid vehicles control problem but with different constraints. In PHEV applications, the larger ESS and the more allowable SOC range (90% to 20%) is available to assist the engine and displace the fuel energy to seek better energy efficient and increase all electric driving range. The ECMS algorithms are shown as follows:

$$x = SoC \quad (6)$$

$$u = P_{bat} \quad (7)$$

$$u'(t) = \arg \min_{P_{bat}, P_{eng}} (J(x, u, \dot{m}_f)) \quad (8)$$

$$P_{whl} = P_{bat} + P_{eng} \quad (9)$$

objective function (10),

$$J(t) = \int_0^{T_f} (\dot{m}_{eng}(t) + \dot{m}_{bat_eq}(t)) dt \quad (10)$$

with constrains (10.a-d),

$$SoC_{\min} \leq SoC(t) \leq SoC_{\max} \quad (10.a)$$

$$T_{mot_min} \leq T_{mot}(t) \leq T_{mot_max} \quad (10.b)$$

$$T_{eng_min} \leq T_{eng}(t) \leq T_{eng_max} \quad (10.c)$$

$$P_{bat_min} \leq P_{bat}(t) \leq P_{bat_max} \quad (10.d)$$

where, P_{bat} is the ESS output power, T_{eng} and T_{mot} are engine and electric motor output torque. The objective function minimizes the total fuel consumption from engine and electric motor fuel equivalent at each time step. J is objective function, x is state of the system (in here is SOC).

The ECMS is relying on the unique operation mode of hybrid electric vehicle in which the energy consumption from the ESS is able to be regenerated and recharged by the engine and generator set [57]. Therefore, battery discharging at any time is equivalent to certain fuel consumption or kinetic energy in the rest of the trip. To weight and qualify the electric consumption, an equivalent fuel consumption function by electric usage is calculated as below:

The electric usage is divided into battery charging and battery discharging with different energy efficiency and losses because of the electric path direction.

Charging,

$$\dot{m}_{bat_eq}(t) = C_{eq} \frac{P_{bat} \times \eta_{elec}}{Q_{lhv}} \quad (11)$$

Discharging,

$$\dot{m}_{bat_eq}(t) = C_{eq} \frac{P_{bat}}{Q_{lhv} \times \eta_{elec}} \quad (12)$$

Where, C_{eq} is the equivalent factor and a detailed calculation in C_{eq} is shown below. The Q_{lhw} is the engine lower heating value which could be treated as the engine fuel burning efficiency or energy density. η_{elec} is the total electric path energy efficiency, which includes motor, inverter and battery energy efficiency.

Equations below explain the calculation of the equivalent factor C_{eq} , which is the most critical factor in the ECMS design. Since the electric consumption is transferred to equivalent fuel consumption, precision in energy conversion will determine the efficiency of the algorithm. For instance, if the equivalent factor is lower than actual, the electric power will be utilized more often since the equivalent fuel consumption is lower. But the actual energy weighing is much higher than estimated, the SOC cannot maintain in the ideal range and causing engine to start more frequently which results in a higher overall fuel consumption.

$$x_1 = \frac{SoC(t) - SoC_{tar} / 2}{\Delta SoC / 2} \quad (11.a)$$

$$K_p = 1 - x_1^3 \quad (11.b)$$

$$x_2(t) = 0.01 \times (SoC_{tar} - SoC(t)) + 0.99x_2(t - \delta t) \quad (11.c)$$

$$K_i = 1 + \tanh(12 \times x_2) \quad (11.d)$$

$$C_{eq} = C_{neq} \times K_p \times K_i \quad (11.e)$$

Where C_{neq} is nominal equivalent factor that needs to be tuned for specific driving cycle or requires adaptive method in order to result in a better performance.

The input to the ECMS algorithm is total power demand at wheels, then the ECMS searches for the best power split between the engine and battery that minimizes the equivalent fuel consumption. In a PHEV energy optimization, the objective function might also consider the effects of battery energy consumption such as the electricity cost, overall emissions (from power generation and gasoline) etc. ECMS regulates SOC at a constant reference point with minimum fuel consumption. These control strategies that

shown in Figure 29 enables real time processing speed with the dSPACE MicroAutobox II on-board vehicle supervisory controller.

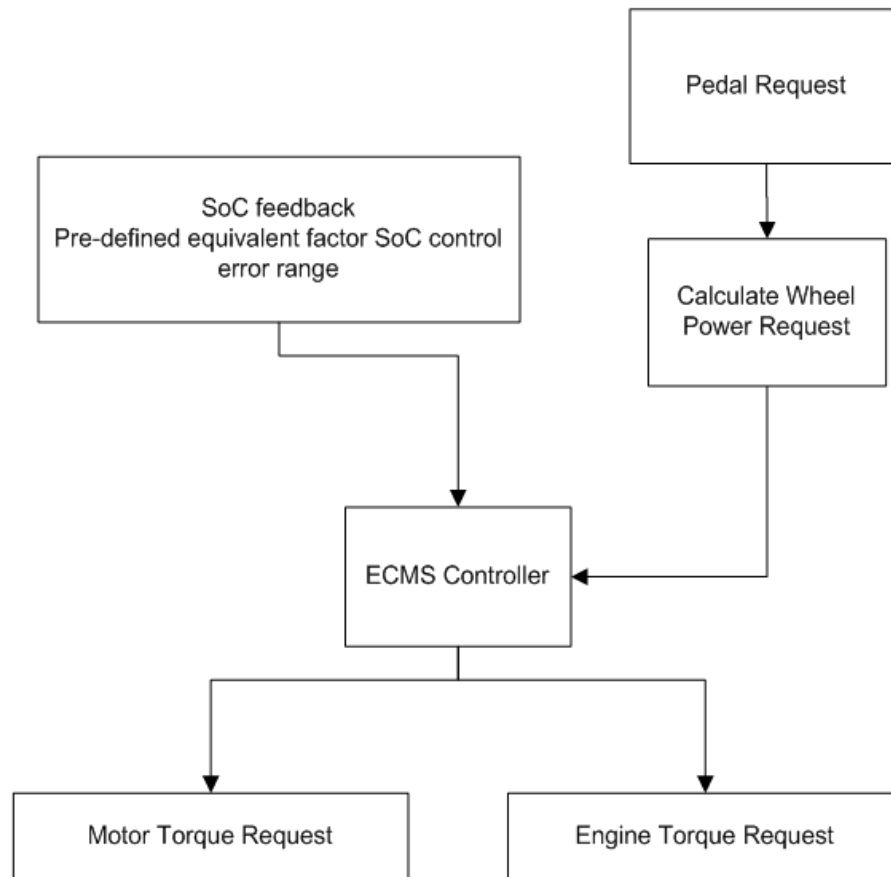


Figure 29: ECMS Control System Scheme

4.6.3. Global Optimization Methods

To further understanding the control strategy effects in powertrain fuel efficiency and the series-parallel architecture's potential, the comparison work was also done including global optimization methods. Two optimal algorithms were taken into comparison - the Pontryagin's Minimum Principle (PMP) based sub-global optimal method with real-time processing ability and the Dynamic Programming (DP) method. The controller and control strategies were developed and modeled by UVic green vehicle researcher, Ph.D. candidate Jackie Dong.

The implementation of the PMP based global optimization method is mainly relying on the fact that the global optimal solution of the objective function is also the solution of the minimized Hamiltonian function at each calculation step. In this plug-in series-parallel multi-regime hybrid electric powertrain architecture, the objective function is subtracted to the minimization of the well-to-wheel fuel consumption while considering both petroleum fuel and electric energy usage. During the simulation, the cost function uses a dynamic constrains for components, such as engine torque range or battery charging rates. With the dynamic constrains and drivability concern, this PMP based optimization method is suitable for on-board real-time application.

The comparison of the global optimization DP method is implemented by using MATLAB M-script. The physical vehicle powertrain plant model is built using backward-looking modeling method, and is coded with identical variables and mathematic calculation to form each powertrain components which makes it a fair comparison between the three control strategies/algorithms from previous section to the DP algorithm.

The fundamental idea of dynamic programming is to utilize battery power as the control variable while keeping battery SOC as state variable. The searching method of DP includes every possible optimal trajectory from the components operational field to realize the global optimal search and control. The DP divides the whole driving cycle into discrete segments/nodes and determines the optimal node combination between the initial and final state, which results in a true global optimal that can serves as benchmark value. An example of the DP searching method is shown in Figure 30. Meanwhile, the DP also helps in developing and calibrating control system and strategy by analyzing and extracting rules and control thresholds from the DP results trajectory.

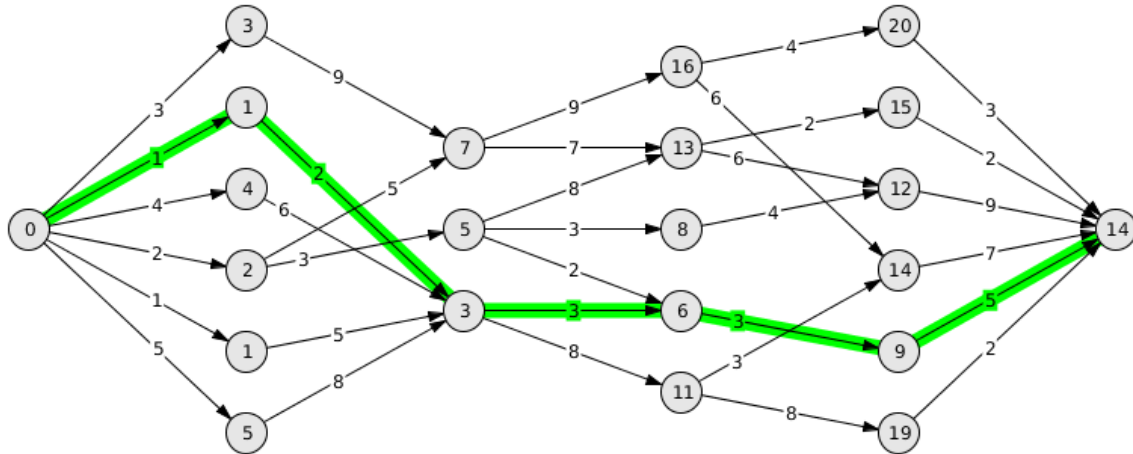


Figure 30: Dynamic Programming Searching Trajectory

4.6.4. Control Strategies Effects Study

In this work, the effects of different control strategies toward certain vehicle powertrain system were studied using MBD techniques. The influence of strategies or control algorithms to fuel consumptions was compared with powertrain and controller modeling as well as simulations in MATLAB/Simulink environment. Simulations were based on the simplified power loss series-parallel powertrain model to perform rapid fuel economy estimation and control algorithms development.

The comparison simulation results as shown in both Table 4 and Table 5 indicated the design optimization potential in fuel saving. In Jackie Dong's comparison work, the baseline plant model and rule-based controller are identical to the one explained in previous section, which allows a fair comparison between the local optimal methods and global optimal methods.

Table 4: FUEL CONSUMPTIONS WITH DIFFERENT CONTROL STRATEGIES

	20 times of UDDS (Lge/100km)	20 times of HWFET (Lge/100km)	20 times of US06 (Lge/100km)
Rule-based	4.558	3.083	6.857
ECMS	4.418	3.013	6.709
Improvement	3.17%	2.32%	2.21%

Table 5: OPTIMAL CONTROL SIMULATION RESULTS FOR UDDS CYCLE [JD]

	Fuel Consumption (L/100km)	Delta SOC	Fuel Improvement	Computation Time
Online Rule-based	3.920	-0.00717	(baseline)	10s
Online PMP	3.724	0.60%	4.39 %	262.51s
Offline DP	3.611	0	7.63%	22475.38s (6.24h)

The manually tuned rule-based controller, which serves as a baseline in this control algorithms comparison work, operated and performed well for each drive cycle in the simulation. In general, the engine optimal energy efficiency curve will guarantee the fuel efficiency from ICE regardless of the high power and frequent start and stop situations. In compare to the component level optimization, the ECMS consider powertrain system fuel efficiency at every operation nodes for each drive cycle. It searches the best power distribution between ICE and electric machines to reach minimum equivalent fuel consumption for the entire propulsion system and results in an average 2-3% fuel consumption improvement comparing to the rule-based control strategy. Whereas, the ECMS optimization searching method cannot robustly find the global minima point for every drive cycles and nodes, especially in the highly nonlinear optimization problems, such as the hybrid electric powertrain system, that contains a large number of local minima. Such that it is required that global optimal searching method is not restricted by fuel minimization for each node but consider the best solution, the best trajectory for the entire drive cycle. The real-time processing PMP based algorithm is a trajectory based sub-global optimization method. Adaptive costate for finding the minimization of PMP and Hamiltonian value was developed and modeled by Jackie Dong in order to perform a quick processing and real-time implementation ability. The PMP based method shows significant improvement, 4.39% less in fuel consumption, comparing to the rule-based controller, and the computation time comparison proved the possibility in real-time application. Finally, the offline DP method gives the best fuel economy improvement, which could also consider as the benchmark and the series parallel architecture theoretical fuel economy with current components configuration. The DP reaches absolute zero in delta SOC, and results in 7.63% fuel consumption improvement in the

UDDS drive cycle. Unfortunately, the drawback of DP, more than 6 hour of computation time, keeps this global optimization method from real-time applications. Even though the DP cannot serve as the best solution in hybrid electric powertrain control optimization method, the different control algorithms and strategies effects study shows a large gaps (around 3% in fuel consumption saving) between the current optimization method with real-time ability, the PMP based optimal method, to the offline benchmark DP method. The results present the merit from the highly flexibility series-parallel multi-regime hybrid electric architecture and encourage further research and development in advanced hybrid electric powertrain control strategies and algorithms.

4.7. Control System Calibration

MBD method as explained in chapter three provided the opportunity in rapid algorithm development and calibration. The rule-based control system and strategy in previous chapter explained the basic logic for vehicle operation functioning. Control strategies and algorithms can greatly affect powertrain energy efficiency which will results in petroleum fuel consumption. To develop and calibrate a proper strategy for vehicle supervisory controller requires control method optimizations. Simplified vehicle powertrain plant model enables fast processing while keeping a relevant close behavior comparing with the physical vehicle, which makes it a perfect optimization platform.

Fuel efficiency and emission reduction play a major role in control system design and development process, and are included as design objectives in many design efforts. Making design decisions which relate to the fuel efficiency and performance objectives of vehicles simultaneously lead to contradictory attributes which requires trade-offs and weight in each objectives. As an example, increasing powertrain components size can lead to the fast vehicle acceleration performance, but will add additional probability of increased fuel consumption and increase vehicle curb weight. Increasing the CD range without adding additional battery pack will results in more fuel consumptions in certain distance, but if the CD range meets daily driving distance can also reduce the total fuel efficiency by not driving in CS mode (which commonly results in a large fuel consumption regardless optimal control strategies). Understanding the interactions between design decision attributes can thusly be observed as multifaceted.

4.7.1. Optimization Method - Genetic Algorithm

Genetic Algorithm (GA) is a stochastic global general-purpose search and optimization method based on the process of Darwin's Theory of Evolution and is a mimic in natural selection. The search method behaves as an evolutionary population in which the fittest member (the best solution in each generation) survives and replicates and weak members are eliminated. This optimization search can be divided into eight sections: population representation, initialization, objective and fitness functions, selection, recombination, mutation, reinsertion and termination.

The Genetic Algorithm starts with a number of populations and changing them during iterations of selection, attempts to converge on the most ideal solution. Through iterative process, the population evolves by generates offspring *using* crossover and mutation technique. The crossover will split two chromosomes and combining one half of each chromosome with the other pair. And mutation flips one bit of a chromosome. After that, the environment delivers predefined fitness criteria for new search points, this will evaluates the population and the fit ones are kept while the others are discarded. The iteration process will repeats until one chromosome reaches the best fitness and taken as the optimal solution of the problem.

The code below shows the Genetic Algorithm method:

```

t = 0;
Initialize P (t);
Evaluate P (t);
While (t < t_max) do;
    t = t + 1;
    Select P (t);
Reproduce P (t);
    Evaluate P (t);
End;
End;

```

Where P (t) is the population function and t is time. The initialize set up includes the initialization process where the initial population P (0) is generated. The evaluate step uses objective functions to determine population fitness. The select step, based on the information about the fitness of the population, uses a selection method to determine

which individuals of the population will be chosen to reproduce. The reproduce step includes information recombination and mutation steps. The GA program will keep search until the termination criteria (reaches t_{max} time) are met.

4.7.2. Application of Genetic Algorithm

In this optimal design, the main target is to calibrate an ideal CD range by tuning control variable of engine assist power threshold. The control purpose is by increasing or decreasing the threshold power to control the engine on/off frequency in charge depletion mode, in that way to enlarge or reduce the total CD range. A predefined driving cycle, UDDS, is used in this calibration to fulfill vehicle performance requirement. Meanwhile, two control variables for the Series-parallel and Parallel mode transition threshold were also calibrated by the global optimization method. In the control state machine, a vehicle load power requirement and vehicle speed will be treated as indicators to decide current vehicle state and the ideal driving mode. As the two driving mode will results in different powertrain energy efficiency with various driving condition, a global search for the best solution for mode transition is a perfect method in optimizing and further reducing fuel consumption. For instance, in city driving condition, frequent start/stop and low speed will greatly reduce powertrain energy efficiency in parallel mode since the engine directly connect to front shaft through transmission. Low shaft speed and torque moved engine operation area to a less efficient zone. Whereas, in series-parallel mode, engine will couple BAS motor to charging the ESS in the same situation in order to move to a higher energy efficiency operation area and to increase the overall powertrain energy efficiency.

Table 6: CONTROL STRATEGY CALIBRATION VARIABLES

Control Variables	Engine On Power	Series-Parallel Speed	Series-Parallel Power
Constrains	[15,55] kW	[5,20] m/s	[15,25] kW

Global optimization calibration of the control strategy variables were listed in Table 6. The optimization problem was solved by Genetic Algorithm modeled and coded in MATLAB and Simulink. In this application, a power loss quasi-static Simulink model of the series-parallel plug-in hybrid electric vehicle powertrain model was used. The

simulation used two iteration of the UDSS driving cycle in consider of the driving load situation in both city and highway. Genetic algorithms method is the most suitable global searching method in this application since the optimization routines are widespread and the objective function is discontinuous (PHEV powertrain system) with unknown local minima.

A random initialized population is generated for algorithm process shown as Figure 31. Through the crossover and mutation process, the selected population evolves over time. For each generation, individuals are valued with objective functions (fuel equivalent consumption) and are either terminated or reproduced accordingly, with a higher weighting of reproduction fitness values.

The mixed energy source of plug-in hybrid vehicles requires a methodology for blending both the petroleum energy consumption and electricity consumption into a combine energy consumption with fuel consumption units. The fuel equivalent consumption is then calculated by utilizing the relative energy density of fuel and electric density method as shown in (13).

$$L_{ge}/100km = \frac{(L_g + kWh_{elec}/8.895)}{d} \quad (13)$$

where L_{ge} is equivalent gasoline consumption, L_g is actual gasoline consumption and kWh_{elec} is electrical energy consumption, d is the total drive cycle distance in simulation.

After fifty generation of the nature selection process, the population gradually converges toward optimal trait until a final solution is found. Final solution conditions are identified by converging criteria and a fifty generational limit on the simulation.

Initial Population	Initial Population Fitness (Equivalent Fuel Consumption)
101001010010010100000000	$f(4.088235, 7.901961) = 7.525469$
1110111010100000110110001	$f(5.233333, 17.627451) = 7.189437$
1011011010100000010001011	$f(4.354902, 17.549020) = 7.239742$
10000111001111011111110	$f(3.617647, 9.784314) = 7.281645$
111101010100010111111100	$f(5.343137, 10.411765) = 7.208845$
100111000011011010000101	$f(3.947059, 9.235294) = 7.538435$
001111011101011000010001	$f(2.456863, 21.784314) = 7.937032$
001011011000101011100001	$f(2.205882, 15.823529) = 7.493739$
001110000001000001111110	$f(2.378431, 6.254902) = 8.028872$
101011011001010101110011	$f(4.213725, 16.686275) = 7.327772$
001001001100001100010010	$f(2.064706, 20.294118) = 8.134886$
001110100000100000010000	$f(2.409804, 5.627451) = 7.725286$
011011101000110001010011	$f(3.225490, 15.980392) = 7.495855$
011111001010010000100100	$f(3.445098, 17.862745) = 7.530967$
00011111110101010101110	$f(1.986275, 23.352941) = 7.939786$
100011010011110100110111	$f(3.711765, 9.784314) = 7.410490$
001110110101000101001000	$f(2.425490, 11.352941) = 7.882721$
100001001100011010010100	$f(3.570588, 20.529412) = 7.281458$
001001101110101110101101	$f(2.096078, 23.431373) = 7.950015$
001110101000011110000011	$f(2.409804, 15.588235) = 7.830523$

Figure 31: Initial Population and Fitness Value

In this control variables optimization, the GA fitness function is defined as the equivalent fuel consumption over the UDDS driving cycle and the vehicle powertrain system as objective function. To perform a comparative simulation results, a non-optimized rule-based controller was taken into simulation. Human experience tuned control variables were implemented in the rule-based controller: 35kW in engine on power, 18kW and 15 m/s vehicle speed in Series-Parallel mode threshold.

4.7.3. Simulation and Optimization Results Analysis

After 50 generations of GA searching method, the fitness value in each generation gradually converged into a best solution point as shown in Figure 32.

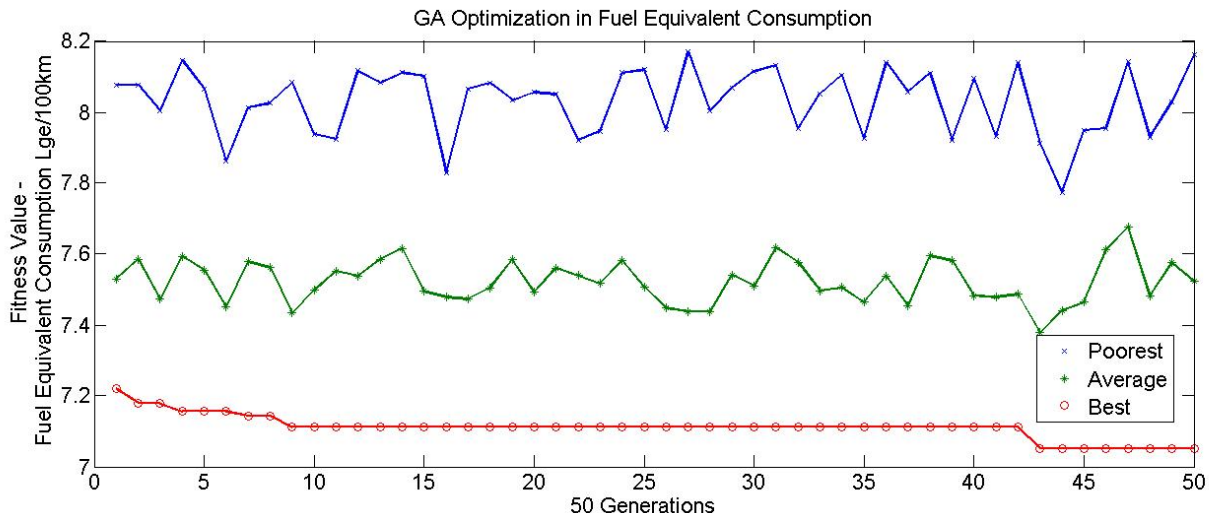


Figure 32: Genetic Algorithm Searching Point for Each Generation

The calibration of the controlled variables resulting from running the global optimization is shown in Table 7. These control variables reached the best overall equivalent fuel consumption over the UDDS drive cycle compared to the baseline controller.

Table 7: GA OPTIMIZED AND BASELINE CONTROL VARIABLES

Control Variables	Baseline Control Model	GA Optimized
Engine On Power	35 kW	34.765 kW

Figure 33 illustrates the energy storage system (ESS) state of charge (SOC) simulation results during two UDDS drive cycles using the GA optimized controller and the non-optimized rule-based controller, zoom in figure of the CD range was shown in Figure 34.

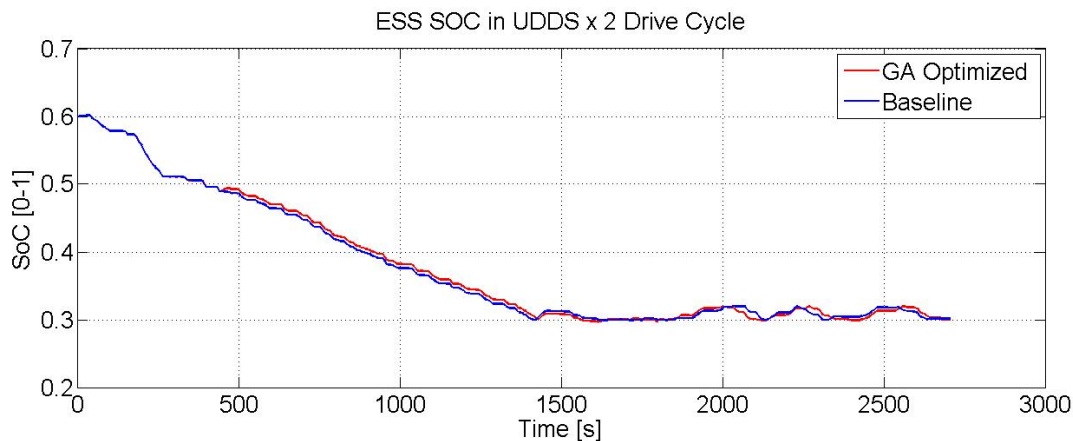


Figure 33: ESS SOC Simulation Results Comparison

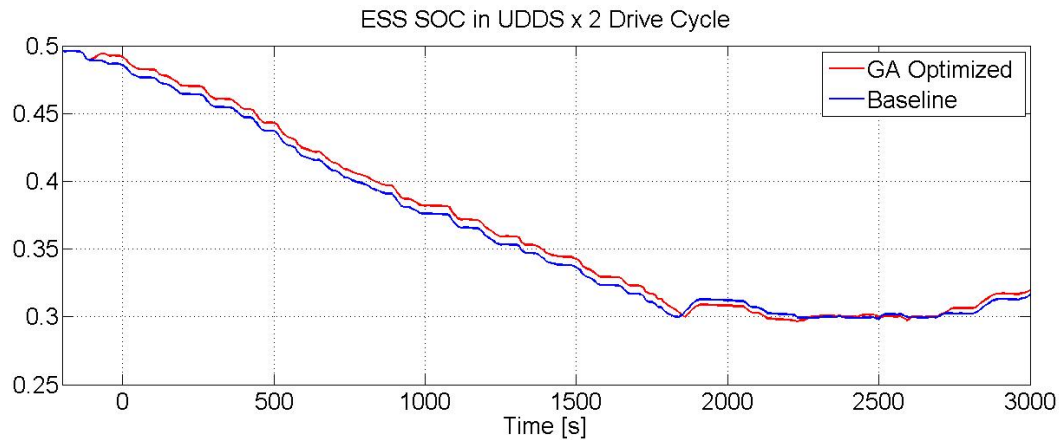


Figure 34: ESS SOC Simulation Results Comparison Zoomed-in Curve

As can be seen in the zoomed in SOC comparison results figure, with the GA optimized control variables searched the optimal design area to find the global optimal point that enlarge the CD range while keep the end of SOC in the same level as the non-optimal controller. At the same time, the mode transitioning logic also tuned for the certain drive cycle (UDDS in this application), higher powertrain energy efficiency was achieved by optimized mode shifts from series-parallel mode to parallel mode.

4.8. Simulation

The vehicle performances, fuel economy and emissions of SPMR-PHEV were investigated under rule-based control strategies and US06-City driving cycles using SPMR PHEV simulation model. The impacts of different vehicle mass and driving distance on fuel economy and emissions of SPMR-PHEV were studied by simulations under different cases.

4.8.1. Vehicle Performance Simulation

Vehicle performances will be directly affected by vehicle mass, initial state and state changes of the powertrain components, and so on. The vehicle performance comparison among Prius, Malibu Eco, Parallel 2WD PHEV and SPMR-PHEV were simulated under different scenarios of the above aspects. Table 8 and Table 9 showed the acceleration performance and maximum speed of the four vehicle models under the simulation of total vehicle mass. The vehicle speeds under eight times of US06-City cycle is shown in Figure 33.

Table 8: DIFFERENT MODEL PLATFORM SIMULATION RESULTS

Vehicle Model		Prius-Auto	Prius-Sim	Malibu Eco	SPMR-PHEV
Vehicle Mass (kg)		1449	1449	1589	1948
Acceleration Performance	0-60 mph (s)	10.5	10.4	8.2	7.6
	Distance in 8s (m)	84.7	84.9	106.7	116.9
Top Speed (mph)		104.3	104.5	134.3	144.7

Table 9: VEHICLE PERFORMANCES SIMULATION RESULTS

Vehicle Model		Prius	Malibu Eco	Parallel PHEV	SPMR-PHEV
Vehicle Mass (kg)		1449	1589	1720	1948
Acceleration Performance	0-60 mph (s)	10.5	8.2	8.6	7.6
	Distance in 8s (m)	84.7	106.7	103.3	116.9
Top Speed (mph)		104.3	134.3	110.1	144.7

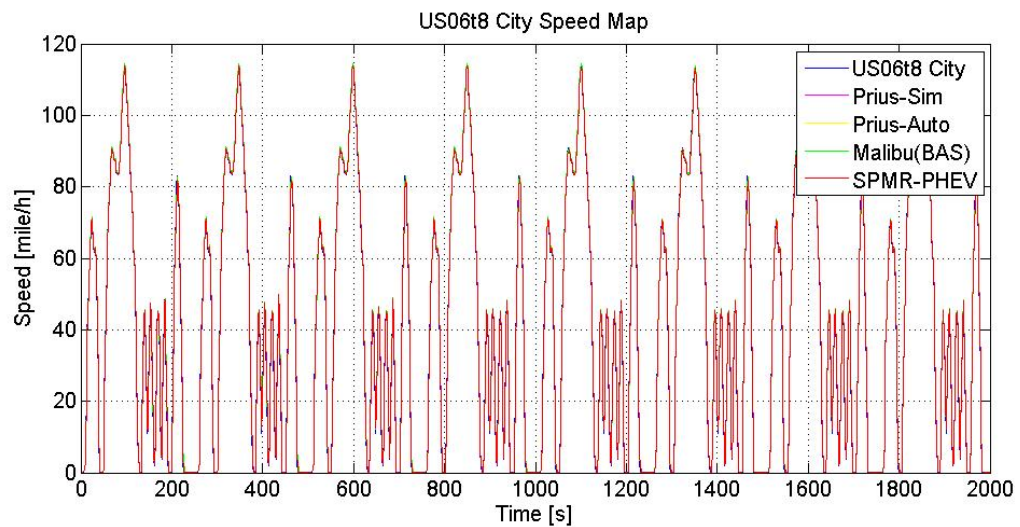
**Figure 35: Vehicle Speeds in Eight Times of US06-City Cycle**

Table 8, Table 9 and Figure 35 indicated that SPMR-PHEV can achieve desired speeds and loads carrying criteria in all driving cycles as non-plug-in HEV. Meanwhile, by comparing the vehicle mass in Table 8 and Table 9, it is clear that the conversion from mild parallel hybrid powertrain system to series-parallel plug-in hybrid powertrain

system adds about 359 kg to the overall weight of the vehicle, which is mainly due to the adoption of larger battery pack and rear traction motor. As a result the SPMR-PHEV has higher fuel consumptions in city driving schedule due to the weight penalty from both battery and electric machines. However, the SPMR-PHEV obtains a much better acceleration performance compared to the non-plug-in hybrid vehicles. This merit comes from a 19.6Ah-Lithium-ion battery pack which could provide higher specific power compared to the typical 6Ah-Lithium-ion battery. Moreover, in a short acceleration circumstance, the rear traction motor could provide higher torque, which results in a boost and better vehicle performance.

4.8.2. Fuel Economy Simulation

The fuel economy of vehicle has much to do with road condition and vehicle mass, for PHEV there are also relationships with all electric driving range and total driving range. The fuel economy and emissions of five vehicles in US06-City-t8 driving cycle was investigated. The simulation results are given by Table 10 and Table 11. The changes of fuel economy and emissions of SPMR-PHEV with weight and driving range increasing were studied. The simulation results are shown in Table 12 and Table 13, respectively.

Table 10: US06-CITY-T8 FUEL ECONOMY RESULTS

Vehicle Model		Prius-Auto	Prius-Sim	Malibu Eco	SPMR-PHEV
Fuel consumption (MPG)		43.21	43.75	33.78	37.84
Emissions	CO g/mile	0.9301	0.9373	1.2098	1.0621
	HC g/mile	0.3289	0.3374	0.4369	0.3756
	NOx g/mile	0.3217	0.3264	0.4145	0.3674

Table 11: US06-CITY-T8 FUEL ECONOMY RESULTS

Vehicle Model		Prius	Malibu Eco	Parallel PHEV	SPMR-PHEV
Fuel consumption (MPG)		43.21	33.78	37.48	37.84
Emissions	CO g/mile	0.9301	1.2098	N/A	1.0621
	HC g/mile	0.3289	0.4369	N/A	0.3756
	NOx g/mile	0.3217	0.4145	N/A	0.3674
	CO ₂ g/mile	273.64	260.37	248.95	247.83

Table 10 and Table 11 show that the fuel economy of SPMR-PHEV in eight times of US06-City cycle is 12.42% and 13.51% lower than Prius-Autonomie and Prius-Simulink model simulation results, but gains 12.02% higher than Malibu Eco. This could be explained as the plug-in hybrid vehicle generally designed for a limit daily economy range, under this range the PHEV is operating in pure electric mode which will achieve low Well-to-Wheel (WTW) fuel consumption.

Table 12: WEIGHT INCREASE IMPACT ON SPMR-PHEV

Vehicle Model		Prius-Auto	Prius-Sim	Malibu Eco	SPMR-PHEV
Vehicle Mass (kg)		1748	1848	1948	2048
Fuel Consumption (mpg)		41.61	40.08	37.84	37.59
Emissions	CO g/mile	0.9621	1.0023	1.0621	1.0744
	HC g/mile	0.3412	0.3589	0.3756	0.3880
	NOx g/mile	0.3318	0.3416	0.3674	0.3623

Table 13: DISTANCE INCREASE IMPACT ON SPMR-PHEV

Vehicle Model		Prius-Auto	Prius-Sim	Malibu Eco	SPMR-PHEV
Range (mile)		11.44	17.14	22.85	28.56
Fuel consumption (MPG)		N/A	57.56	37.84	31.55
Emissions	CO g/mile	0	0.6980	1.0621	1.2739
	HC g/mile	0	0.2484	0.3756	0.4507
	NOx g/mile	0	0.2397	0.3674	0.4406

Table 12 denotes that without modification of vehicle configuration, an increase in vehicle mass will result in an increment of fuel consumption and emissions level. For PHEV, the battery capacity has to be optimized by balancing the vehicle mass and all electric driving range.

As can be observed from Table 13, a pure electric drive of the PHEV in first 11.44 miles results in no fuel consumption with zero emissions. Whereas, for driving distances more than 11.44 miles, the fuel consumption and emission levels of the PHEV tend to rise. It can be noted that for a 17.14 miles distance the fuel consumption and emissions are about

half compared to the non-plug-in HEV, and for 28.56 miles daily range the fuel consumption of a plug-in HEV is close to that of a non-plug-in HEV because at this driving distance PHEV will operate as conventional HEV.

In order to know how the all electric driving range and total driving range of PHEV impact on the fuel economy and emissions, the battery SOC of Prius, Malibu Eco, Parallel 2WD PHEV and SPMR-PHEV in eight times of US06-City Cycle were calculated by simulations. The simulation results were showed in Figure 36, Figure 37 and Figure 38.

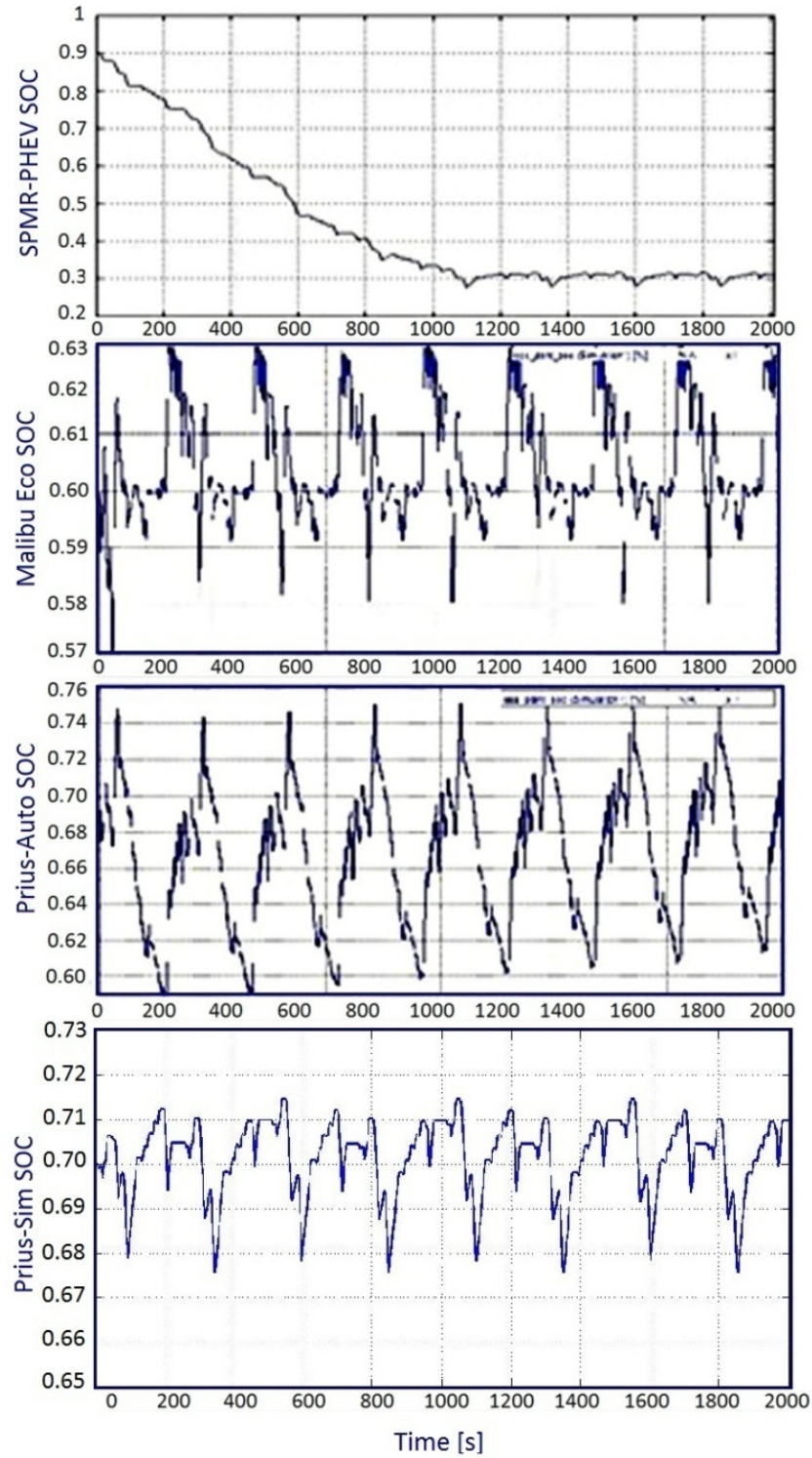


Figure 36: Four Models Battery SOC in Eight Times of US06-City Cycle

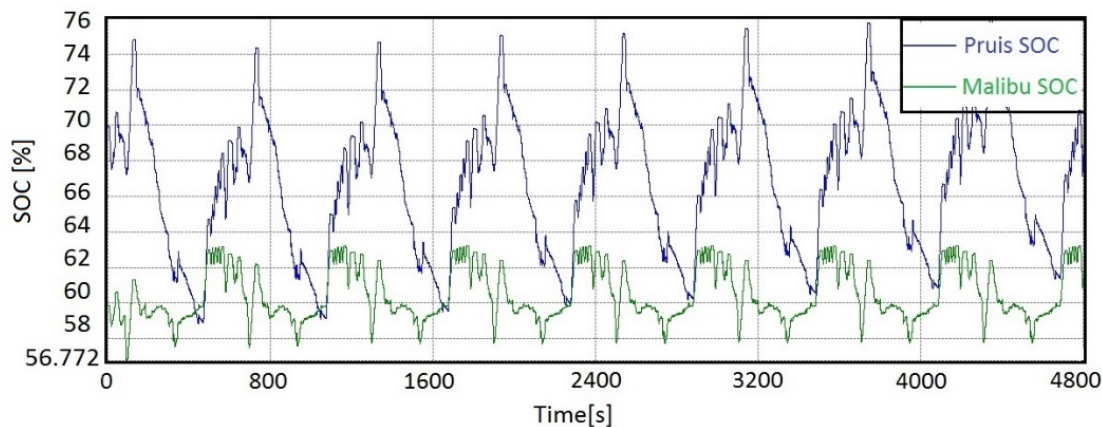


Figure 37: Malibu and Prius Battery SOC in Eight Times of US06-City Cycle

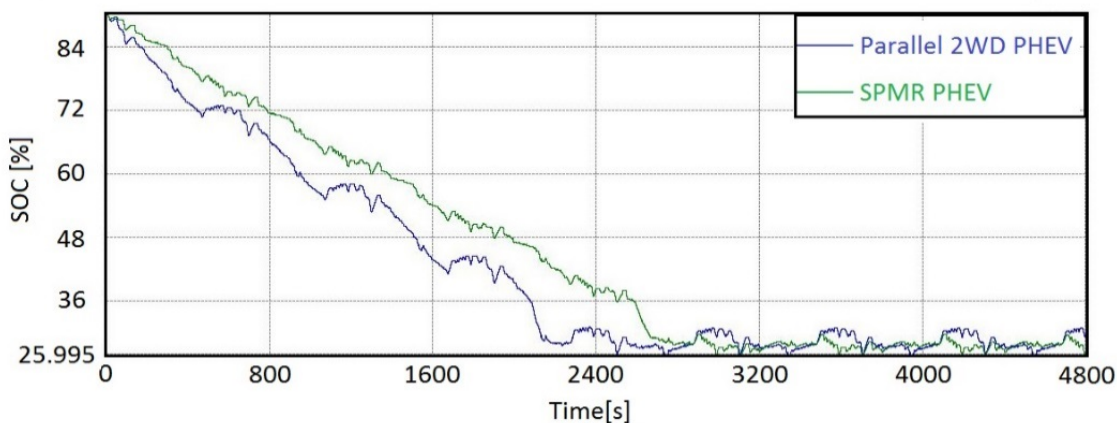


Figure 38: Vehicle Battery SOC in Eight Times of US06-City Cycle

While in eight times of US06-City cycle, it can be observed from Figure 36 that after 1100 seconds the SPMR-PHEV turns to Charge Sustain mode, which could result in low energy efficiency. Meanwhile, by looking through the Autonomie modeling processes, calculations are done by setting driving conditions into static look-up tables with constant values, which could result in a higher performance and fuel economy than actual vehicle. Whereas in the Prius-Simulink model, a self-developed rule based control strategy proves to achieve a higher fuel economy, but the emissions is not good enough as SPMR-PHEV. In the eight times of US06-City cycle, the SPMR-PHEV first operated in a pure electric drive mode which results in zero fuel consumption. Figure 38 shows the plot of SOC of each vehicle, and in charge sustaining mode of SPMR-PHEV, the state of

charge is maintained with the limits prescribed by the EMS, which tends to optimize engine operating points to achieve low fuel consumptions and emissions.

As stated above, the fuel economy and emission of a PHEV are dependent on all electric driving range. If a PHEV runs within EV range, the fuel tank would never have to be filled. If a PHEV runs a distance for twice its all electric range, the fuel consumption is almost cut to half compared to conventional HEV. If a PHEV runs a distance for more than twice its all electric range, it is not considered economical taking into account of the extra battery cost and the increase of vehicle weight. Plug-in hybrid vehicles are generally designed for a limit daily economy range, under this range a PHEV is operating in pure electric mode which will achieve low Well-to-Wheel (WTW) fuel consumption and emissions.

Chapter 5 Powertrain System Study of Race Car PHEV

5.1. Formula Hybrid Competition Program

The Formula Hybrid program is an automotive and auto sport engineering design challenge for the undergraduate and graduate college and university students. The program was started at the Thayer School of Engineering at Dartmouth College, and sponsored by the Society of Automotive Engineers. Formula Hybrid competition is a spinoff of the Formula SAE competition based on hybrid vehicle technology.

The Formula Hybrid student automotive design competition encourages the development of hybrid automotive drive trains with an emphasis on energy efficiency in a high-performance application. Improved energy efficiency in an automotive drive system can be used to increase fuel economy, and performance. The competition requires teams to design, build and race an open-wheel, single-seat race car. This car must conform to a formula which emphasizes drive train innovation and fuel efficiency in a high-performance application.

The competition evaluates the car's performance through acceleration, autocross and endurance events. Additionally, the team is judged on its project success through evaluation of the Project Management tactics and how the team undertook throughout the build of the Formula Hybrid vehicle. Along with the overall engineering design of the car, points are awarded based on whether a feature was designing from scratch or implemented with off-the-shelf components.

The UVic Formula Hybrid vehicle is an open-wheel single-seat plug-in hybrid electric race car. The vehicle is currently being designed from the ground up to provide high performance and exceptional energy efficiency in a single, highly integrated package. Figure 39 shows UVic Formula Hybrid I race car built by our team.

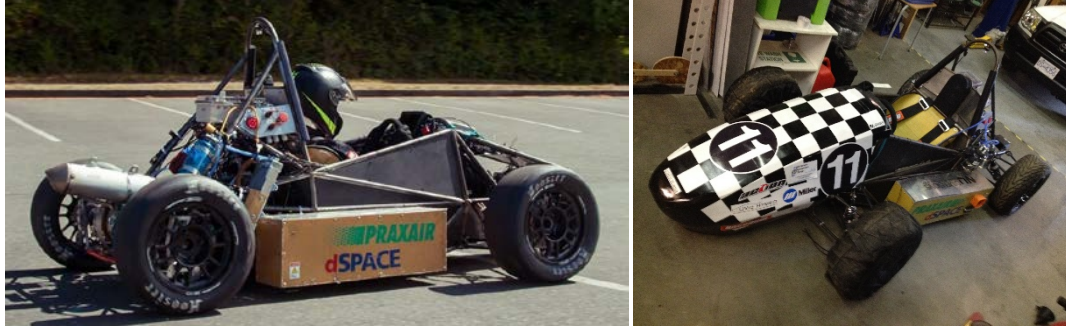


Figure 39: UVic Formula Hybrid I

5.2. Vehicle Powertrain Configuration and Key Parameters

Figure 40 presents a parallel architecture that was implemented into Formula Hybrid racing car for student team competition, UVic Formula Hybrid I. To achieve high power to weight ratio and load transform, steel alloy tube frame, fiber glass body, and light engine and other components from light-weight sport motorcycles were chosen, including a 250cc 37Hp KTM fuel engine couple with 5-speed transmission, 75-5 67Hp Z-Force electric machine, and a 96V 2.8 kWh Li-ion battery pack.

Different from a generic passenger car, this Formula Hybrid I race car utilizes rear-mount RWD instead of AWD or FWD. The reason to choose RWD with all powertrain components mount in the back is to achieve better weight transfer during hard acceleration. Rear driving wheel will gain more normal force that allows higher maximum propulsion torque. Without complicated drive shaft joints at the front wheels, the vehicle has a smaller turning radius. The even weight distribution may also improve the vehicle handling with more road grip during cornering [58].

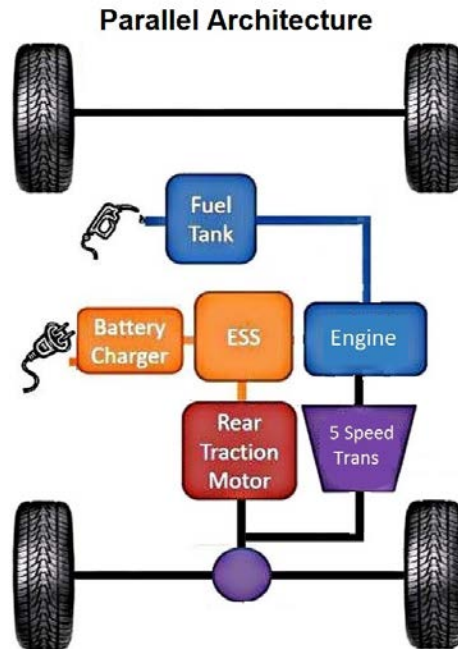


Figure 40: Rear Wheel Drive Post-transmission Parallel Architecture

The Formula Hybrid I car has a post-trans parallel powertrain architecture in which the engine is coupled with the electric machine after transmission to a different ratio final drive. Different from a conventional passenger vehicle, the major concerns of a race car is to reduce curb weight for superior performance. Complex powertrain with extra weight to gain powertrain energy efficiency and fuel economy falls to lower priority in this case. Normally, a parallel hybrid powertrain would gain additional weight due to its added transmission, comparing with the Trans-less series hybrid powertrain. However, in this race car hybrid powertrain, a light small-ratio transmission is coupled with a large electric motor to produce enough torque during acceleration with minimum weight addition. Meanwhile, the parallel hybrid electric powertrain avoids the inherent Mechanical-to-Electrical and Electrical-to-Mechanical energy conversion losses of the series or series-parallel architectures, enabling better fuel efficiency and wider range endurance.

5.3. Vehicle Dynamics Model

Selection on different types of powertrain system model is mainly based on the type of vehicle application. For a race car, such as the Formula Hybrid vehicle, the major concerns are vehicle dynamics, acceleration, and braking performance. To better capture

and predict the dynamic responses of the vehicle, a low-frequency vehicle powertrain dynamics model shown in Figure 41 was built using the dSPACE Automotive Simulation Models (ASM) tool [59]. This model includes a detailed vehicle drivetrain with both longitudinal and lateral dynamics. With this low-frequency model, between 1 and 10 Hz, it is possible to model and calibrate advanced engine start-stop control, transmission gear shifts control, and traction control.

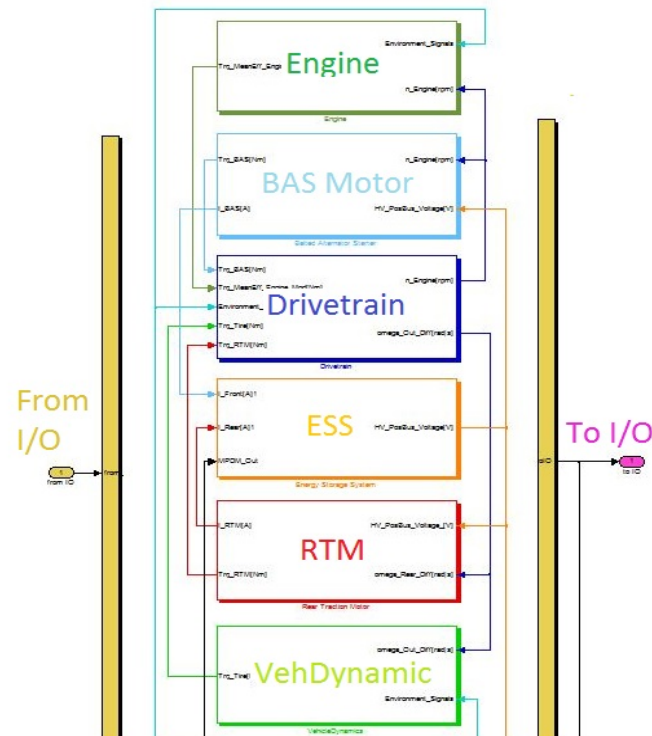


Figure 41: Vehicle Dynamic Models

The low-frequency Formula Hybrid powertrain model utilizes the same driver model in the quasi-static passenger vehicle model. The differences and critical criteria of Formula Hybrid Vehicle's powertrain model development and simulation setup are discussed in the following sections.

The low-frequency powertrain dynamics model introduced for the Formula Hybrid Vehicle was designed and modeled using dSPACE ASM modeling tools. High fidelity powertrain component models were built, which includes a four stroke one cylinder engine, 5-speed sequential transmission with controlled shifter pistons and friction clutch

as well as traction motor/generator and ESS. Components experimental testing data were collected from sponsors, key features and physic dynamics and kinematics like engine's four stroke responses, motor's inertia and response time and transmission shifter's damping were modeled. In this way, the low-frequency high fidelity powertrain model was able to simulate gear shifts, engine power detune control, engine rev control and vehicle traction control as well.

Besides vehicle high fidelity powertrain component models, different control schemes for acceleration, autocross and endurance tests were implemented. The launch control maintains engine speed into a narrow area where the engine could output maximum torque to the rear axle. Power shift transmission control also greatly improves acceleration performance, this control strategies allows shifter piston hold in a pre-shifting status while any engine power dropping will results in a rapid gear shift. To better serve the autocross test, the traction control was also imbedded into the controller. This traction control uses PID control to monitor wheel slip-ratio, control output realized by engine retarding ignition and decreasing throttle position as well as negative torque output from electric motor. The Rule-based load-leveling energy management strategy was also used in this model to control powertrain system operation in either electric drive mode or hybrid mode to minimize total energy consumption during endurance test. The electric traction motor/generator operates only in high power demand or start from a low speed zone. The control scheme tuned motor engaging power and speed to maximize overall powertrain energy efficiency while maintaining a high acceleration performance in the meantime.

5.4. Model Validation

The model is validated by comparing with vehicle on-board testing data. The driver pedal input and vehicle speed were gathered as model inputs references. Vehicle data was collected by Vector data logger from vehicle EV road tests. The detailed sub-components ECU is not build in the vehicle plant model, therefore the components throttle request will transferred as direct torque request to sub-components. The control strategies of the physical vehicle powertrain and simulation model are identical. The results are shown in Figure 42 and Figure 43.

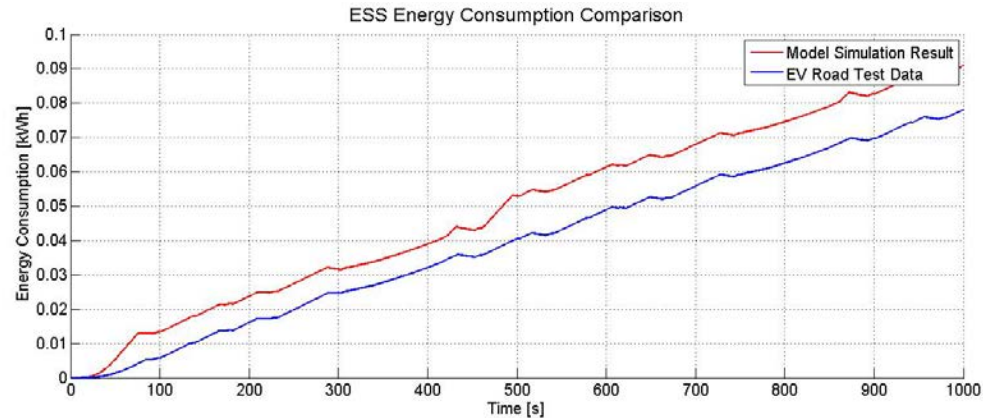


Figure 42: ESS Energy Consumption Comparison of MIL and Road Test

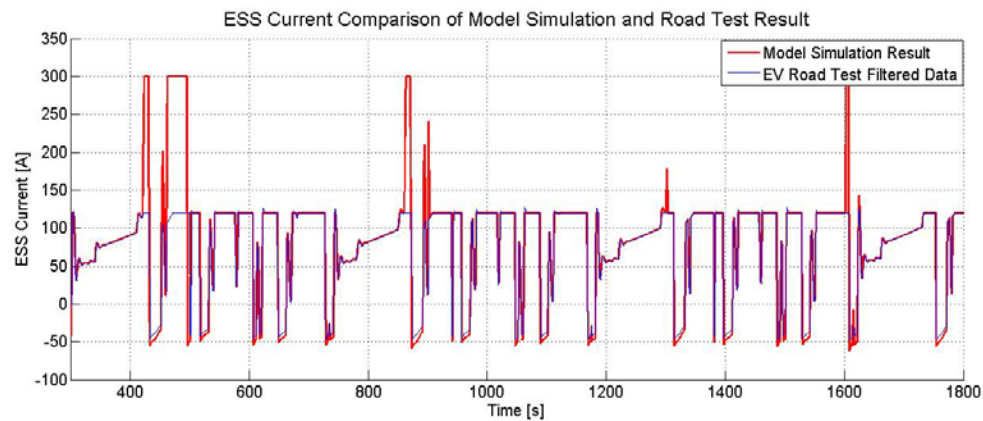


Figure 43: ESS Current Comparison of MIL and Road Test

As can be observed from Figure 43, the components response is difference during aggressive acceleration period where the dynamic effects restrictions of the model is less accurate. But the overall ESS energy consumption is relatively similar since the component level diagnostics and output limit is controlled under highly safety range that the driver torque demand can be satisfied by the powertrain. The components torque responds is close enough as the output torque error is less than 10%.

5.5. Vehicle Dynamics Control

The traction control technique has been widely used in auto sport area and implemented to most commercial vehicles in recent years. This control system helps to eliminate wheel spinning and loss of traction during vehicle launching or low speed boosting [60].

The traction control system (TCS) controls and monitors the vehicle wheel slip ratio, and utilizing powertrain components, such as ICE or electric motor in hybrid powertrain, to maintain an optimum value which could maximize the tire traction force. Usually, the control methods including engine retarding ignition, engine crank shaft braking, throttle control, electric motor braking and electric hydraulic braking. Whereas, the optimum slip ratio for a certain tire with same conditions (the same temperature, tire pressure, road surface and etc.) does not remain constant and varies depending on vehicle dynamics effect. A typical longitudinal vehicle tractive effort coefficient map is shown in Figure 44 as an example. It is an engineering design and control challenge to predict the actual optimal slip ratio dynamically under all driving situations without prior knowledge of road or tire conditions.

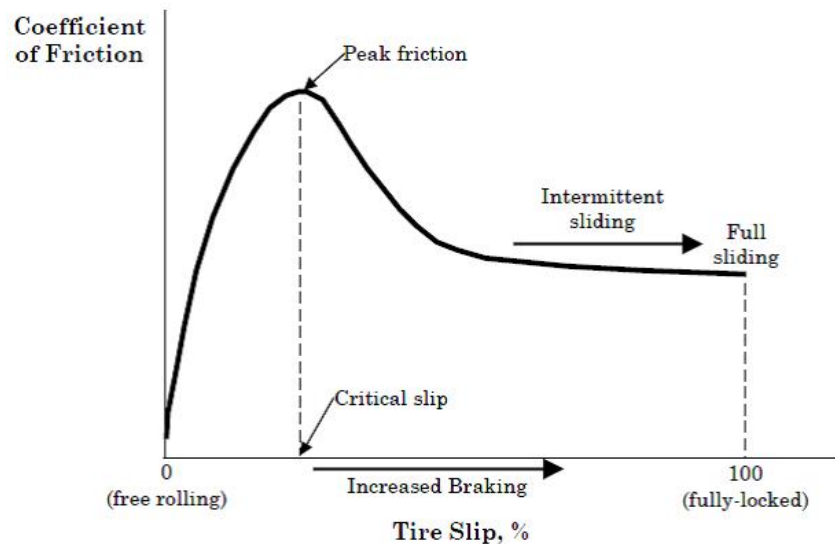


Figure 44: Typical Longitudinal Wheel Slip and Traction Coefficient Map

In this work, an adaptive traction control is modeled in MATLAB/Simulink environment as shown in Figure 45. This control scheme is designed for acceleration event in Formula Hybrid competition, and especially developed for vehicle launching and quick acceleration. During the vehicle launch process, the TCS continuously monitor the vehicle wheel slip ratio. If the acceleration rate is not in optimal point, a controlled increment torque pulse will be generated mainly electric motor to increase the slip ratio until the acceleration reaches maximum at current state. Further controlled slip ratio increment will results in a decrease of acceleration rate and once the TCS detects the drop

in acceleration rate when adding control increment torque, the TCS will stop generates control torque pulse unless any fast changes in wheel slip ratio.

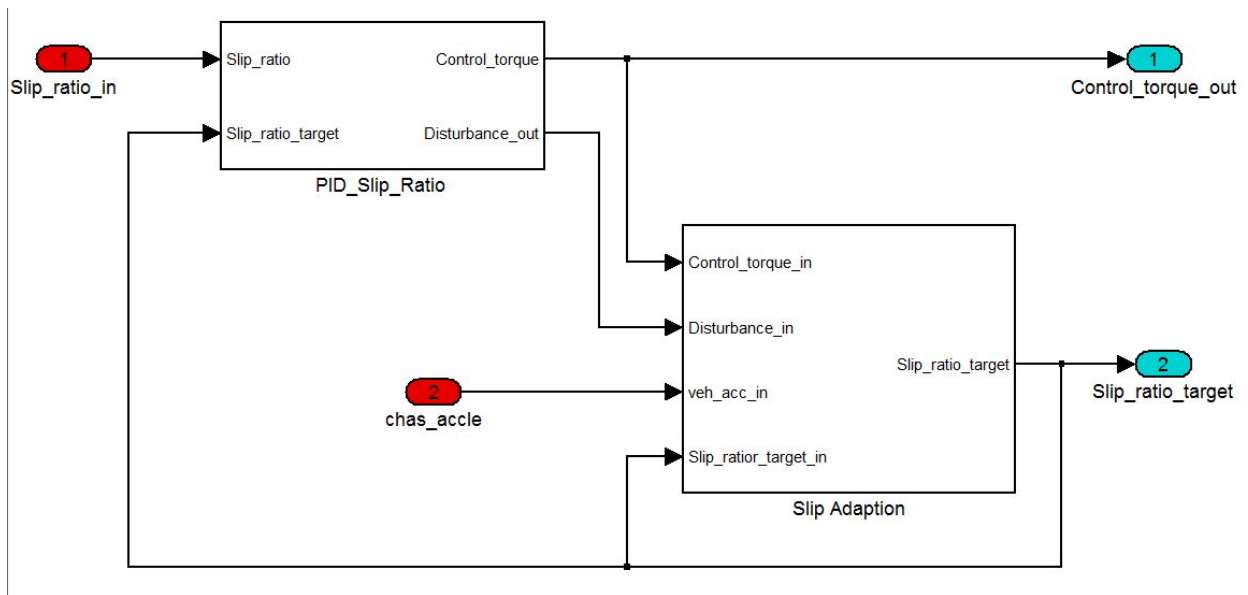


Figure 45: Hybrid Adaptive Traction Control

Detailed control logic is shown in Figure 46. The TCS only activate when sensing an over 80% driver acceleration pedal input and the wheel slip ratio is higher than a preset value. Initially the slip ratio target is set at a relatively high value, usually around 25%. When traction control is enabled, the aggressive wheel spinning will be under control by the control torque provided by ether engine, electric motor or baking pads. Since then, if the pedal is holding over 80%, a predefined small disturbance torque pulse is generated. The detection block then compares to delta slip change versus delta acceleration change and decides whether to increase or decrease the optimal wheel slip ratio target. This small torque pulse loop is continuously executed until the next severe wheel slip ratio change or the traction control is disabled, which keeps the optimum wheel slip ratio tracking.

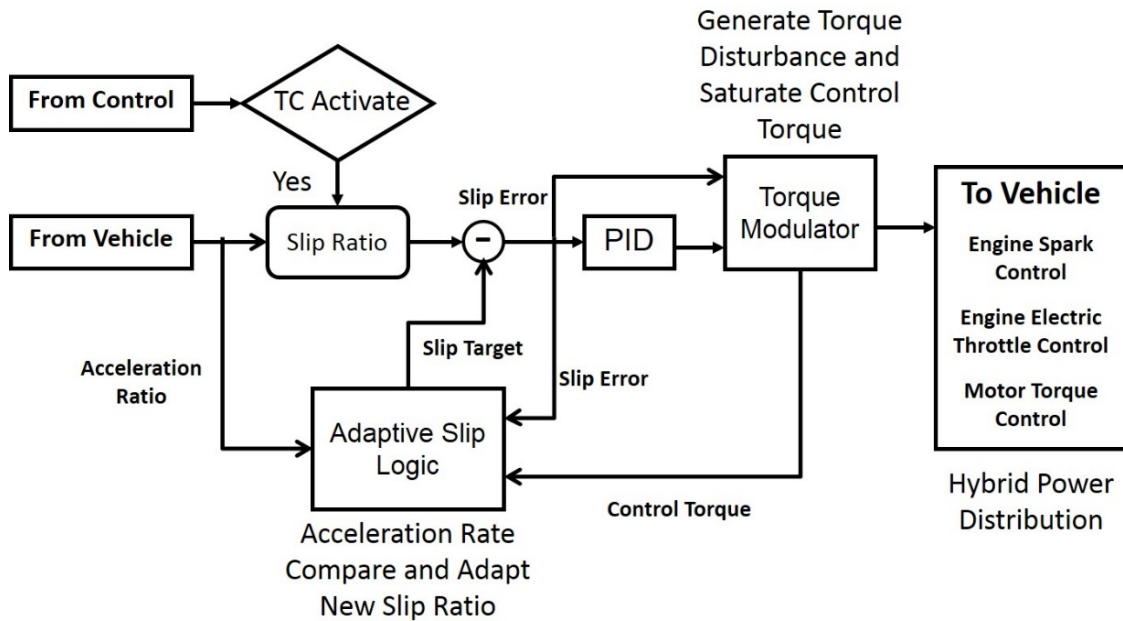


Figure 46: Traction Control Logic

Simulation was performed using MATLAB/Simulink with dSPACE ASM based vehicle plant model. The supervisory controller includes an EMS with basic hybrid electric power distribution function, and the TCS to tests vehicle launching. The simulation purpose is to test the Formula Hybrid launching performance and the differences with and without TCS. The testing is 0 to 100 km/h longitudinal acceleration event based on a 0.75μ road surface, simulation result is shown in Figure 47.

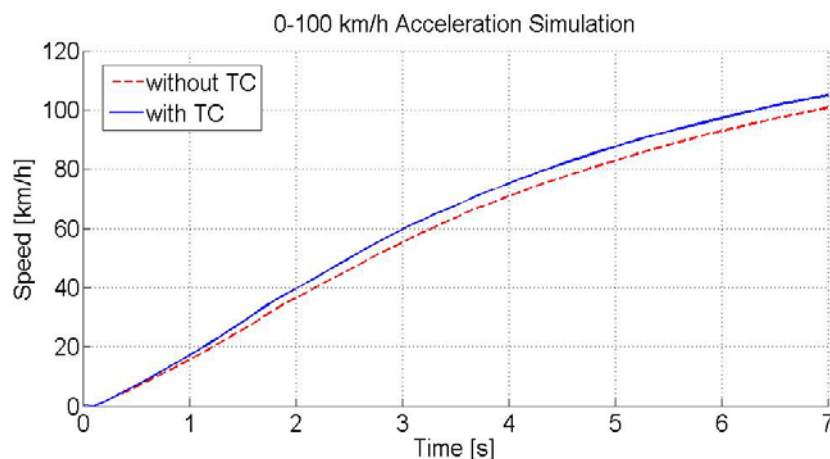


Figure 47: Traction Control Simulation

As the simulation result denotes in Figure 43, the TCS starting with a same acceleration rate compare to the non-TCS vehicle. After the wheel slip ratio reaches the optimal range

as explained previously, the TCS achieves 0.7 second ahead and 6.3 second in total to reach 100km/h vehicle speed. The ten percent acceleration time differences in largely restricted by the road and tire conditions, the 0.75 μ road surface is generally ideal situation while in lower μ applications, such as snow or ice surface, the TCS will results in a tremendous improvement compare to non-TCS controller.

Meanwhile, different with conventional traction control, the TCS in this application involves with hybrid torque actuation and road condition adaptive. The control torque can be performed either through engine control, electric motor control or brake by wire control methods. The hybrid torque actuation increased system complexity but in another way reduced the risk of system failure. Since the TCS is a control method to monitor wheel slip ratio, the same theory can also implement in Antilock Braking System (ABS) as a backward application.

Chapter 6 Hybrid Powertrain System Study of Mining Truck

6.1. Background and Design Objective

The project is initiated as a joint effort between the Department of Mechanical Engineering, University of Victoria (UVic), Canada and the Department of Vehicle Engineering, Beijing University of Science and Technology (BUST), China.

As a representative of mining trucks, the vehicle data of the Articulated 35T Underground Dump Truck from BUST is acquired, and a simple series hybrid electric powertrain system is modeled using UVic's existing PHEV generic powertrain modeling platform. This initial study serves as the foundation for defining the research problem and direction in the near future, as well as example for communicating the research initiative and benefit to potential research collaborators and industrial partners.



Figure 48: Articulated 35T Underground Dump Truck CAD Model

Mining dump trucks have been the most popular vehicles which are applied in most of the surface mines over the past decades. Meanwhile, the requirement of these vehicles are still rising steadily [61]. These vehicles usually worked under harsh environmental conditions, strict safety issues as well as high energy consumption. The energy consumption in mining dump trucks account for about 32% of the total energy

requirement in open pit mines [61]. Gibson have found that the elimination of the mining trucks idles time in a typical 20-truck opencast mine results in saving 14500gal/year which means not only GHG can be reduced, but also the cost of mining can be saved.

Advanced hybrid electric powertrain can provide a promising solution to significantly reduce their fuel consumption and Greenhouse Gas emissions, if proper design and controls are developed. With vehicle hybridization and electrification, the implementation of the state of the art into mining truck enables controlling the balance of engine power, grid dissipation and battery charging or discharging will results in the advantages of energy savings, GHG reduction, and cost reduction. Therefore, it is significantly imperative to make a study about the fuel consumption performance of mining dump trucks based on different hybrid electric powertrain configurations.

In this work, the alternative powertrain systems of a commercial mining dump truck are modeled with UVic hybrid electric powertrain modeling platform developed using MATLAB/Simulink. The powertrain energy efficiency and costs of three powertrain configurations, conventional with diesel engine, diesel-electric with electric grid power, and series hybrid electric architectures were investigated.

The objective of this study is to explore the powertrain energy efficiency improvement potential of mining dump trucks electrification and hybridization considering different hybrid electric vehicle powertrain configurations. This project requires design hybrid electric mining truck powertrain to reduce the fuel consumption based on retrofit and re-engineering the current off-highway vehicles, especially large tonnage mining trucks. Results from a preliminary comparative study on vehicle performance, fuel economy and Greenhouse Gas emissions (GHGs) of alternative powertrain under typical drive and load cycles are produced and analyzed. This study forms the foundation for further research and developments of advanced hybrid electric powertrain system designs for mining dump trucks and similar vehicles.

6.2. Configuration of the Mining Truck

The hybrid electric powertrain system of a mining dump truck based on conventional powertrain has been modeled using the design parameters from a glider vehicle and the

fuel efficiency data of a diesel engine. The vehicle technical specification of the glider vehicle is illustrated as in Table 14.

Table 14: VEHICLE TECHNICAL SPECIFICATION

Mass, kg	23,000
GVRW, kg	58,000
Top speed, km/h	55
Grade-ability at 20 km/h, %	15
Powertrain Configuration	Conventional/Mechanical
Fuel Capacity, L	390
Rated Engine Peak Power, kW	261
Peak Engine Torque, Nm	1559 (at 1300 rpm)
Transmission and Gear Ratio	5.182; 3.191; 2.021; 1.383; 1
Final Drive Ratio	12.5
Tires	18-25 32 PR
Wheel Radius, m	0.835.5

At present the dominant powertrain propulsion system for mining dump trucks are based on conventional diesel engine and diesel engine and generator set with or without electric power grid assist, also known as diesel-electric configuration. These configurations were carried out on trucks from Caterpillar, Komatsu, Belaz, and many other industrial companies.

This study evaluated the benefits in powertrain hybridization by adding Energy Storage System (ESS) to the diesel-electric vehicle, and conducts a study using MBD method to estimate fuel consumption and emission improvements. Three typical powertrain systems were taken into comparison and modeled for simulations, the conventional diesel engine configuration, diesel-electric configuration and series hybrid electric powertrain system. For diesel-electric and series hybrid electric configuration, similar rule-based load following control strategies were implemented.

As shown in Figure 49, the diesel engine solely drives the vehicle in the conventional powertrain configuration. The engine providing torque through a multi-gear transmission and passes the large ratio final drive to drive the shaft. Even with a multi-gear ratio in the transmission to adjust engine operation speed, the huge energy losses from wide engine working area and transmission results in low energy efficient of the entire powertrain system.

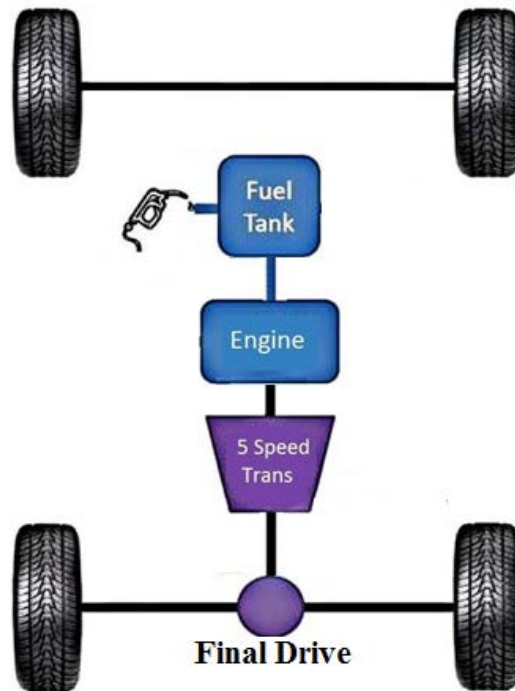


Figure 49: Conventional Mining Truck Configuration

The diesel-electric configuration is also known as AC electric drives technology. This configuration, shown in Figure 50, is well established in the giant shovels and draglines vehicles and has been installed in surface mines trucks worldwide. In diesel-electric configuration, the diesel engine powered generator to provide electricity and rectified into DC power through power electronics to drive the electric machine. During vehicle braking, the AC wheel hub motors operate as generator to convert kinetic energy into electric power. The braking chopper switches the excess energy to be dissipated to the

resistor grid, resulting in heat. While the mechanical braking system will assist AC motors to produce braking torque.

The AC drive allows the engine to be decoupled with the drive wheels and utilizes generator to control diesel engine operation at higher energy efficiency region. Wheel hub motors provide much higher low speed torque without sacrificing energy efficiency losses, and the application of the transformation from conventional diesel configuration to diesel-electric configuration is relatively simple. Whereas, the energy transmit efficiency is decreased during the multi energy conversion processes.

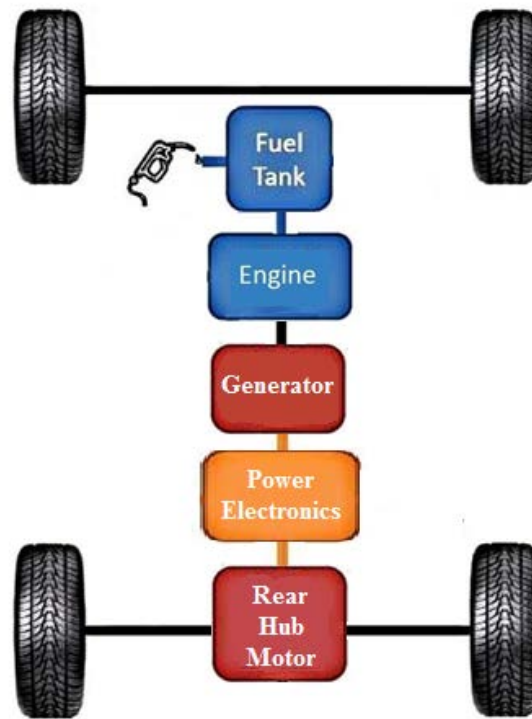


Figure 50: Diesel-Electric Mining Truck Configuration

In this work, the configuration comparison simulation also considered series hybrid electric architecture. Figure 51 shows the powertrain components in series architecture, the basic function in series architecture is the same with diesel-electric configuration. However, the additional ESS will create a buffer between the engine-generator set to the electric wheel hub motor drives. Further engine speed or power control could be implemented to optimize engine operational points and the power output between engine-

generator set and load requirement will be balanced by the ESS. Meanwhile, the capability in perform regenerative braking, turning kinetic energy into electric energy that consumed at resistor-grid as heat in diesel-electric configuration, can be recaptured by switching the wheel hub motors to generators, and generates electric energy further convert into chemical energy storage in the ESS.

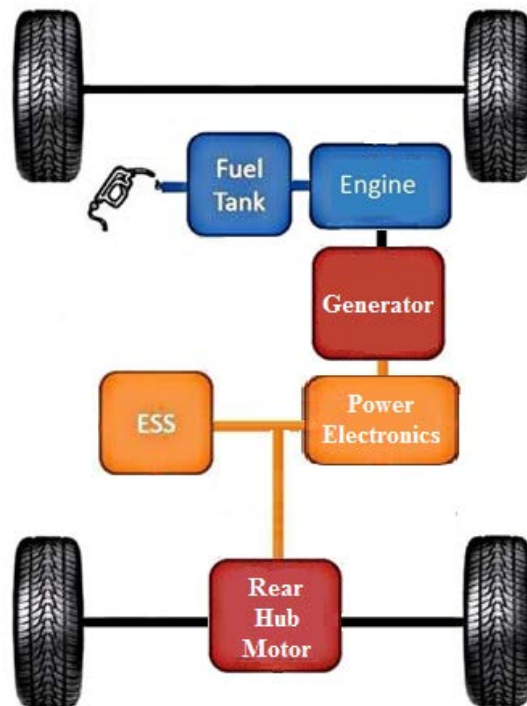


Figure 51: Series Mining Truck Architecture

6.3. Powertrain Modeling and Simulation

6.3.1. Driving Cycle and Load Pattern

The mining truck in this simulation setup runs continuously in open field with a fixed working cycle and 35,000 kg loads at moderate speed. Two repeated UDDS Truck driving cycles with scaled speed under 55 km/h was used as vehicle driving reference. The drive cycle is shown in Figure 52. The load pattern will mimic the real world situation, where the vehicle starts with unload state and after one cycle ended, the vehicle will be fully loaded with mines and return.

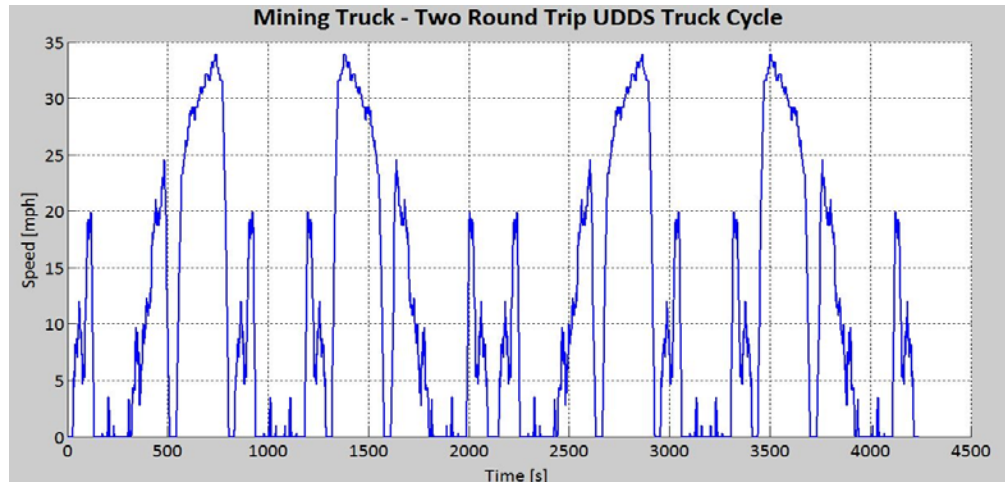


Figure 52: Round Trip Heavy-Duty Drive Cycle

6.3.2. Vehicle Theoretical Models

The vehicle powertrain models were built in MATLAB/Simulink environment for powertrain energy efficiency analysis and control strategy development. Three different powertrain architectures as explained in previous section were modeled using simplified power loss hybrid electric powertrain model platform to perform a rapid model based design development process. ESS, electric drive path and vehicle dynamics are based on scaled models from EcoCAR 2 power loss powertrain plant model since this study is mainly focus on powertrain energy efficiency study and require less in representative physical model details. The modeling information of the diesel engine is shown as follows.

The engine model is based on the 4-Stroke Cummins QSM11 with Electronic diesel engine. Engine fuel consumption rate and emissions rate as well as operational characteristics are modeled using lookup tables. The engine working speed and output power are inputs to the emission model, which are used to calculate the fuel consumption rate and emissions rate, respectively. Figure 54 shows the engine fuel consumption map and Figure 53 indicates the detail of engine operating curve.

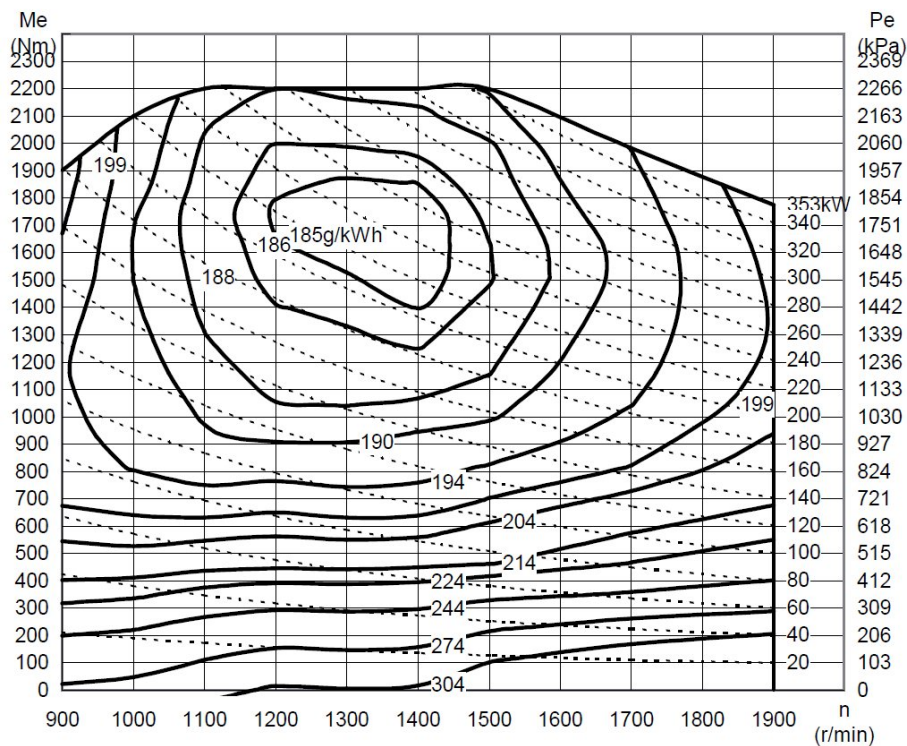


Figure 53: Diesel Engine Torque-Speed Map with Fuel Efficiency

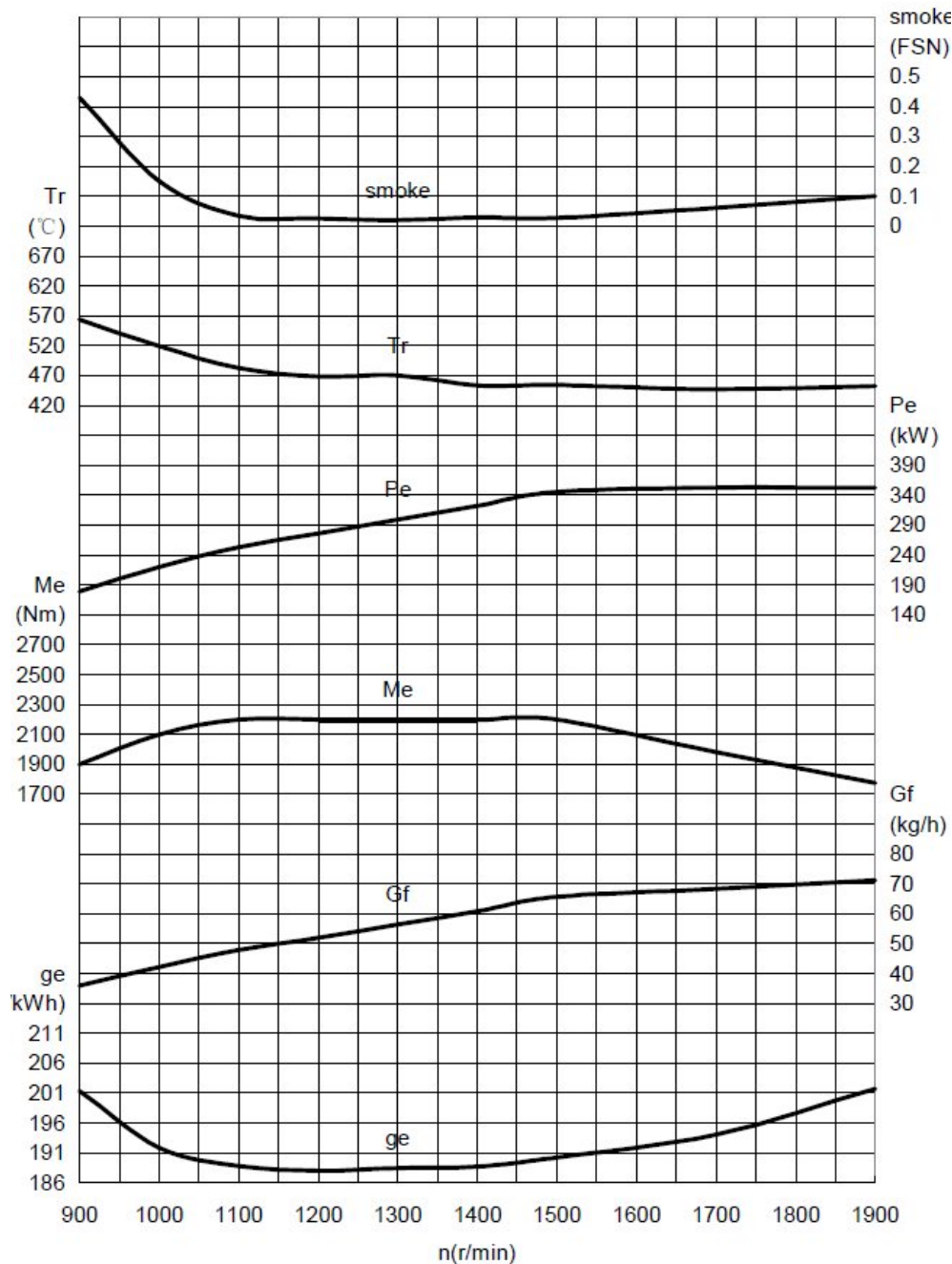


Figure 54: Diesel Engine Operational Map

6.3.3. Preliminary Results and Analysis

Simulations are done using round trip heavy-duty UDDS drive cycle and Table 15 presents the relative fuel economy improvements of the three proposed powertrain configurations. The diesel engine suffers from poor operational energy efficiency area including low speed with heavy load conditions, results in the lowest fuel economy of

41.05 L/100km as well as GHG emissions of 2,489 g/km. Compare to the conventional powertrain configuration, the diesel-electric powertrain configuration allows engine to operate at higher speed and energy efficiency zone regardless the vehicle speed and load. The change in engine operation area shows improvement in overall powertrain energy efficiency. Mechanical transmission losses is avoided by the decoupling of engine to the drive shaft, whereas the mechanical to electric and electric to mechanical multiple power conversion losses are increased. As well, the diesel engine still operates at the unfavorable energy efficiency region in occasional vehicle high power situation. The series hybrid electric powertrain architecture using the ESS as the energy buffer and engine speed control method to maintain the engine operational point in the highest working zone. The advantages of the conversion of series architecture also include the easy transformation from diesel-electric configuration to series configuration.

Table 15: UDDS TRUCK CYCLE SIMULATION COMPARISON RESULTS

	Relative Improvements		Fuel Consumptions	GHG Emissions
	Fuel Consumption	GHG Emissions	L/100km	g/km
Conventional	Baseline	baseline	56.25	2489
Diesel-Electric	8.92%	8.3%	51.23	2283
Series Hybrid	19.36%	10.8%	45.36	2221

According to the simulation results of the three proposed vehicle configurations, the implementation of the series hybrid electric architecture could dramatically reduce petroleum fuel consumption by more than 130L per day for each all-day operating mining truck. Significantly environmental impact from the conventional diesel powered mining truck will be controlled and minimized by the vehicle powertrain hybridization and electrification.

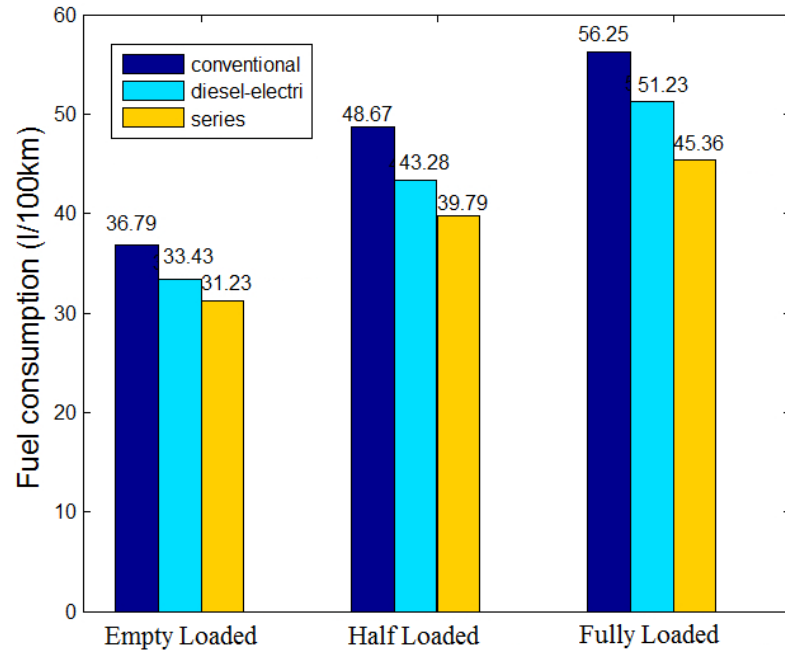


Figure 55: Fuel Consumption Results with Different Load Conditions

Limitations to the hybrid electric powertrain configuration include electric operation voltage and battery life cycle length. To form a PHEV or HEV configuration, the battery pack voltage in the series hybrid powertrain system requires more than 600V and can cause potential safety issues. The ESS working under heavy loaded charging and discharging scenario requires further bench tests to ensure the battery life cycle and the robust system.

Chapter 7 Conclusions and Future Work

7.1. Different Vehicular Application Comparison and Analysis

7.1.1. Passenger Car Key Features

7.1.1.1. Architecture Flexibility

The great flexibility provided by the series-parallel multi-regime architecture can be treated as one of the key features. The series-parallel architecture includes several driving modes to face the various road conditions in the real-world driving situations. Advantages of this system are that it provides both series and parallel system depending on the driving conditions. At higher speeds the system will function in parallel mode, routing power from the engine directly to the wheels, where the engine operates near its highest energy efficiency area. In frequent stop-and-go and city driving conditions the system will operate in series mode, routing power from engine to generator and reaching a higher powertrain overall energy efficiency by engine speed and power control. Therefore, this is the most fuel efficient design.

While the added benefits of both series hybrids and parallel hybrids are achieved for this configuration, control algorithms become very complex because of the large number of driving possibilities available. Multi-regime hybrid powertrain technologies not only refer to the powertrain architecture, but also involve powertrain system control. Multi-regime designs can have any combination of series, parallel, and power-split configurations, which allow the system control unit to select suitable transmission configurations with widely ranging characteristics and advantages according to the vehicle load and powertrain components. The control strategies could make the vehicle get optimal performance and better fuel economy.

7.1.1.2. Safety and Drivability

Safety and drivability are always prior criteria in commercial passenger vehicle design. In this advanced vehicle technology hybrid electric powertrain and control system design, the safety factor is also a key feature. Safety design and testing were carried by a creep torque design and control system diagnostics function.

The creep torque control strategy is specifically designed for vehicle start and stop function and increasing safety. A low propulsion torque was implied to the rear axle from RTM when the vehicle is under a certain speed, the creep torque will adjust by the brake pedal position and ESS SOC. Creep torque will allow engine to stop instead of idling to further improve fuel economy and prevent accident in hill starting.

For better driving experience and increase powertrain system reliability, the operation of vehicle mode transition is been controlled and restricted by a state transition unit that the control system actively managing and monitoring the vehicle components state by reading the Ready Set Go (RSG) and Emergency Power Off (EPO) feedback. The mode transition unit enhanced the drivability by providing smooth transition and functions to restrict in frequent mode transition. As the global optimization method may searches the best trajectory without any restrict function in mode transition speed, the highly complex architecture will results in a frequent mode transition that jeopardise both powertrain components and driver.

The mode transition unit using a rule based shifting logic that filtered the frequent transition decision from the EMS while maintain a constant acceleration performance and avoid any kind of jerk in transition process. In a typical transition process, the previous working components will not suddenly shutdown. Instead, the transition unit implementing a Gauss Error Function that gradually reduces the torque request from the target component while making a continuous torque output as the driver expected. The hyperbolic tangent function sustained the idea of torque continuous while remain in simply calculation and reduced the development and troubleshoot time.

7.1.2. Sport Car Key Features

In general racing area, vehicle acceleration, deceleration, cornering and vehicle controllability comprise about ninety-eight percent of the performance. Vehicle gross weight affects the most of vehicle performance. Therefore, the weight minimization for vehicle powertrain system became a major part of the designer's tasks.

The vehicle weight lightness will gain considerable advantages in auto sport acceleration event and endurance. In this study, the power to weight calibrations simulated the

combination of two sets of motors and three sets of ESS scheme under two operation conditions. Simulation results of acceleration performance are shown in Table 16 and Table 17.

Table 16: POWER TO WEIGHT RATIO STUDY (0-60 MPH TIME)

Motor Power (hp)	ESS			
	Capacity (kWh)	2.4	3.4	4.4
	Weight (kg)	21.9	25.3	30.4
46	Acceleration Time(sec)	5.6	5.2	4.8
67	Acceleration Time(sec)	5.7	5.3	4.8

The electric motor used in this specific design is Zero motor Z-Force 75-5, capable of as much as 46 hp and 80 ft-lbs of torque. Parametric study was taken with Z-Force 75-7, which provides 67 hp and 106 ft-lbs maximum power output. With three sets of ESS varies from 2.4 kWh to 4.4 kWh, a generic vehicle power to weight ratio simulation were done by using acceleration event drive cycle.

Table 17: POWER TO WEIGHT RATIO STUDY (75 METERS TIME)

Motor Power (hp)	ESS			
	Capacity (kWh)	2.4	3.4	4.4
	Weight (kg)	21.9	25.3	30.4
46	Acceleration Time(sec)	5.2	5.2	5.2
67	Acceleration Time(sec)	5.3	5.2	5.1

The simulation results showed that the most ideal power to weight ratio for the acceleration event was realized by the combination of 46 hp Z-Force 75-5 and 3.4 kWh Li-ion ESS. This combines both consistent acceleration time and keep the investment as low as possible. An ideal longitudinal load transfer was achieved by balancing the front and rear wheel load and the rate of acceleration. This power to weight calibration ensures the rear axle with enough torque to spin the wheel and approaches traction limited

acceleration rate. As well, an even rear weight distribution, 46/54 front to rear, was achieved to produce more forward traction from the rear wheels.

7.1.3. Mining Truck

Vehicle electrification using diesel-electric and hybrid electric powertrain systems can improve fuel efficiency over conventional diesel-only powertrain due to improved engine operation energy efficiency.

Introduction of the simplest form of series hybrid electric powertrain, as well as the addition of a battery ESS and simple power following controls can further improve fuel economy and reduce Greenhouse Gas emissions with modest investments.

The 13.4 kWh Li-ion battery ESS meets the basic hybrid system requirements, enables energy recovery from regenerative braking, and further improves engine working condition, leading to increased powertrain system energy efficiency.

Control strategy plays a crucial role in a hybrid electric powertrain system. More advanced control strategies and real-time optimal control can further improve the energy efficiency, as learnt from our advanced hybrid electric powertrain research.

A significant merit of this new design is that the fuel consumption and long term running costs have been dropped sharply compared with the conventional mining truck. Furthermore, although the grade ability and maximum speed of new design decrease to 15.3% and 53.9km/h respectively, they still satisfy the design specifications. The results reveal that the series mining truck has great potential to explore and produce in the market.

7.1.3.1. Vehicle Weight Adaptive Control

The heavy-duty mining truck hybridization is based on engineering retrofit to current truck vehicle, adding additional wheel hub induction motors and energy storage system to the existing drive train to perform multi-drives configuration. The powerful induction motors are capable to provide considerable torque and power for vehicle propulsion from

stop or low speed. While the unknown of truck load and overall weight could result in a non-predict sudden jerk or slides if using a fixed pedal position to power demand ratio.

Unique feature is then defined as the weight adaptive throttle control method, which automatically checks vehicle weight and propulsion system limits (ESS SOC, motor diagnostics) to perform a smooth and unified pedal to acceleration rates ratio in a certain vehicle power demand range.

7.2. Research Contributions

The thesis includes systematic research works on PHEV powertrain and control systems design and development for different vehicular applications using MBD techniques. The major contributions from the research works can be summarized as follows:

A quasi-static simplified power loss model for SPMR-PHEV powertrain was built for the characterization of basic vehicle performance and dynamics, which includes component models of E85 engine, belt-alternator starter (BAS) motor/generator, belt system, energy storage system (ESS), rear traction motor, transmission, and vehicle longitudinal dynamics. This model was validated and evaluated by comparing the simulation results with the relative outputs from high fidelity dSPACE UVic EcoCAR2 model using several industrial standard drive cycles. This model was used to study the effective of the multi-regime architecture and the control strategies effects towards vehicle fuel economy. As a quasi-static model, the powertrain components are modeled simply as power loss tables and provide fast simulation processing speed. The detailed component transient effects and ECU behaviour are not simulated. As a result, the quick run-time and relative simplicity make it a good platform for developing energy management strategies in a manageably isolated, yet relevant simulation framework.

In this work, two control strategies were modeled in Simulink and taken into comparison, which are rule-based load following strategy and equivalent consumption minimization strategy (ECMS). A well-defined state-of-the-art rule-based load-leveling control strategy was designed and built in MATLAB/Simulink environment for SPMR-PHEV vehicle plant model, which could meet the demand of the flexibility of the powertrain architecture with multiple possibilities in electrical and mechanical power paths. In this

rule-based strategy, the calibration is fulfilled according to the SOC of ESS and Engine fuel consumption and energy efficiency data map. It is suitable and flexible as it does not need pre-knowledge of a driving cycle. An Equivalent Consumption Minimization Strategy (ECMS) was also designed for the operation of a PHEV in CS mode. To reach a minimum fuel consumption point, two power sources (ESS and engine) will get combined and generated an equivalent weight for optimization at each time of the calculation. This control strategy take the advantage of larger ESS and the more allowable SOC range (90% to 20%) of PHEV to assist the engine and displace the fuel energy to seek better energy efficient and increase all electric driving range. This control strategy also enables real time processing speed with the dSPACE MicroAutobox II on-board vehicle supervisory controller. The rule-based and ECMS control effects were studied by simulations in MATLAB/Simulink environment. Two global optimization based control strategies online PMP and offline DP were also investigated by simulations in MATLAB/Simulink environment.

A low-frequency powertrain dynamics model introduced for the Formula Hybrid Vehicle was designed and modeled using dSPACE ASM modeling tools. High fidelity powertrain component models were built, which includes a four stroke one cylinder engine, 5-speed sequential transmission with controlled shifter pistons and friction clutch as well as traction motor/generator and ESS. The low-frequency high fidelity powertrain model was able to simulate gear shifts, engine power detune control, engine rev control and vehicle traction control as well. A Rule-based load-leveling energy management strategy was used in this model to control powertrain system operation in either electric drive mode or hybrid mode to minimize total energy consumption during endurance test. An adaptive traction control is modeled in MATLAB/Simulink environment. This control scheme is designed for acceleration event in Formula Hybrid competition, and especially developed for vehicle launching and quick acceleration. The traction control in this application involves with hybrid torque actuation and road condition adaptive. The control torque can be performed either through engine control, electric motor control or brake by wire control methods. The hybrid torque actuation increased system complexity but in another way reduced the risk of system failure. Since the TCS is a control method to monitor

wheel slip ratio, the same theory can also implement in Antilock Braking System (ABS) as a backward application.

This study evaluated the benefits of powertrain hybridization by adding Energy Storage System (ESS) to the diesel-electric vehicle. Three typical powertrain systems were taken into comparison and modeled with UVic hybrid electric powertrain modeling platform developed using MATLAB/Simulink. Three typical powertrain systems include conventional diesel engine configuration, diesel-electric configuration and series hybrid electric powertrain system. The powertrain energy efficiency analyses, control strategy development, estimation of fuel consumption and emission improvements were done by using the above models.

7.3. Future Work

In this thesis, three HEV and PHEV powertrain applications and control strategies were investigated and optimized for better vehicle performance and fuel economy through modeling and simulation. The author also spent much time on simulation platform development. Based on the current research results, the author would give the suggestions on future works for the hybrid powertrain models and the UVic HEV simulation platform improvements.

The current quasi-static PHEV passenger car powertrain Simulink models do not consider transient response of vehicle components and use static efficiency maps and fuel consumption maps for the engine and the motor. The dynamic characteristics of the powertrain need to be further investigated. The exploration of the possible solution to minimize the inaccuracy from the mode transient would be the next step of research focus.

In terms of sport car, the major concerns are vehicle dynamics, acceleration, and braking performance. It is much more important to understand its dynamic characteristics than fuel economy and GHG emissions. Currently a low-frequency vehicle powertrain dynamics model was built using the dSPACE Automotive Simulation Models (ASM) tool. It was able to simulate gear shifts, engine power detune control, engine rev control and vehicle traction control. Further development on full dimensional vehicle dynamic

model could better serve following investigations. Full dimensional nonlinear braking dynamic model may be established to better simulate the tire-road adhesion characteristics for braking control strategy development to improve vehicle braking performance and enhance braking stability. To improve the effectiveness and accuracy of vehicle vibration control, full dimensional nonlinear vibration dynamic model needs to be developed. In this model both driver and passengers should be taken into account.

Currently the UVic HEV simulation platform includes Hardware-in-the-Loop (HIL), Software-in-the-Loop (SIL) and Model-in-the-Loop (MIL) simulation functionality. With the increase of complexity and safety requirements for tomorrow's vehicles, Vehicle-in-the-Loop (VIL) testing will become indispensable for complementing actual driving tests. A HEV powertrain design needs to consider three complex interacting systems including driver, vehicle and environment. The driver and the environment are very important influences for vehicle operating and driving strategies. In order to get optimal vehicle operating and driving strategies, Vehicle-in-the-Loop testing could offer a more convenient and accurate development platform by the integration of virtual test and actual vehicle intervened test through the extension of I/O-communication between actual vehicle and hardware-in-the-loop simulation platform. Vehicle-in-the-Loop testing will benefit the faster development of the hybrid adaptive traction control method.

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