Hybrid Controls Development and Optimization of a Fuel Cell Hybrid Powertrain

by

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A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Master of Applied Science

in

Mechanical Engineering

Waterloo, Ontario, Canada, 2012

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The University of Waterloo Alternative Fuels Team's participation in EcoCAR: *The Next Challenge* provided an unparalleled opportunity to execute advanced vehicle technology research with hands on learning and industry leading mentoring from practicing engineers in the automotive industry. This thesis investigates the optimization of the hybrid operating strategy on board the EcoCAR development vehicle. This investigation provides the framework to investigate the pros and cons of different hybrid control strategies, develop the model based design process for controls development in a student team environment and take the learning of this research and apply them to a mule development vehicle.

A primary controls development model was created to simulate software controls before releasing to the vehicle level and served as a tool to evaluate and compare control strategies. The optimization routine was not directly compatible with this model and so a compromise was made to develop a simplified vehicle model in the MATLAB environment that would be useful for observing trends but realizing that the accuracy of the results may not be totally consistent with the real world vehicle. These optimization results were then used to create a new control strategy that was simulated in the original vehicle development model. This new control strategy exhibited a 15% gain in fuel economy over the best case from the literature during an Urban Dynamometer Driving Schedule (UDDS) drive cycle.

Recommendations for future work include adding charge depletion operation to the simulation test cases and improving the accuracy of the optimization model by removing the simplifications that contributed to faster simulation time. This research has also illustrated the wide variability of drive cycles from the mildly aggressive UDDS cycle having 5 kilowatts average propulsion power to the very aggressive US06 cycle having 19 kilowatts average propulsion power and their impact on the efficiency of a particular control strategy. Understanding how to adapt or tune software for particular drive cycle or driver behaviour may lead to an interesting area of research.

Acknowledgements

Thanks to Hal for introducing me to UWAFT and telling me I should stick around to do my masters with the team, and to Mendes, Matty and Winston for pushing me over the edge. The career changing decision I made in 2008 has completely changed my life – without a doubt for the better.

Dedication

To my parents for sticking with me wherever I go.

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Chapter 1

Introduction

1.1 Motivation for this thesis

Interest in solving problems that relate to the world's energy consumption and environmental issues are compelling for many practicing engineers and engineering students. A chance to participate in these efforts was made possible through an Advanced Vehicle Technology Competition (AVTC) series initially developed two decades ago by the United States Department of Energy and partnering automakers. The four year competition, *ChallengeX: Crossover to Sustainable Mobility*, from 2004 to 2008 sparked an interest in the field of advanced vehicle design and specifically the challenging realm of real time control systems for these vehicles.[1] A great opportunity then presented itself when *EcoCAR: The NeXt Challenge,* a three year AVTC competition, became the successor to ChallengeX in 2008. [2] The University of Waterloo Alternative Fuels Team (UWAFT) was tasked with re-engineering a General Motors VUE with the three main objectives:

- Improve energy conversion efficiency;
- Reduce overall well to wheel GHG emissions and petroleum energy use; and,
- Maintain overall consumer appeal.

UWAFT as a team selected and designed a new architecture for the EcoCAR competition classified as a Fuel Cell Plug-in Hybrid Electric Vehicle (FC-PHEV). The challenge to become one of the leading teams in EcoCAR and to show the public there are alternatives to gasoline powered vehicles became strong motivation to develop and optimize the control of this power train with emphasis on real world implementation.

1.2 Objective of the research

The primary objective is to design an optimized control strategy for hybrid power splitting on board the EcoCAR development vehicle.

The secondary objective is to develop and document the model based design process and the optimization strategy and techniques used with the intention of providing a framework for future generations of students to work from.

With advanced vehicles moving to the consumer market, automakers are faced with an increasing number of interrelated and complex control challenges. This research seeks to investigate the implementation of control tasks and software features into a student designed prototype vehicle.

1.3 Thesis Organization

Chapter 1 starts with an introduction including the motivation, objectives and organization of the thesis and document. Chapter 2 provides the literature review and background material pertinent to the later more focused chapters and in some cases provides some starting points for the research. Chapter 3 provides detailed information on the vehicle architecture selected by the team and component specifications required for the later chapters in the paper. Chapter 4 presents the controls development process used including the requirements for the hybrid control strategy. This chapter also describes, in detail, the models used in the controls process and finally the simulation results from initial strategies gathered from the literature and initial engineering estimates using these models. Chapter 5 is dedicated to the optimization process used for the hybrid control strategy including the model simplification and results. The chapter also includes a final strategy created by recognizing patterns from both the initial estimates and the optimization results. Finally the conclusions and recommended future work is contained in Chapter 6.

Chapter 2

Background and Literature Review: Trends in the Automotive Industry

2.1 Automotive trends and Statistics

As a brief justification for the research a few statistics on the energy use in Canada will highlight the overwhelming amounts of energy consumed by road transportation in the form of fossil fuels. In 2007 nearly all road energy is provided by diesel fuel or gasoline shown in Figure 1. To frame transportation sector with respect to all energy consumed in Canada, nearly one third of all energy consumption is a result of transportation (Figure 2). When all of the energy consumption from road based vehicles (buses, cars, light and heavy trucks, motorcycles) is combined it equates to 20% of the total energy consumption in Canada. [3] This is an enormous proportion on its own and does not include rail, air or marine transport.
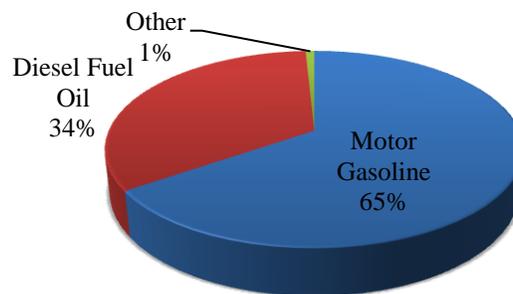
Figure 1: Road Energy Use by Source in Canada (2007)[3]
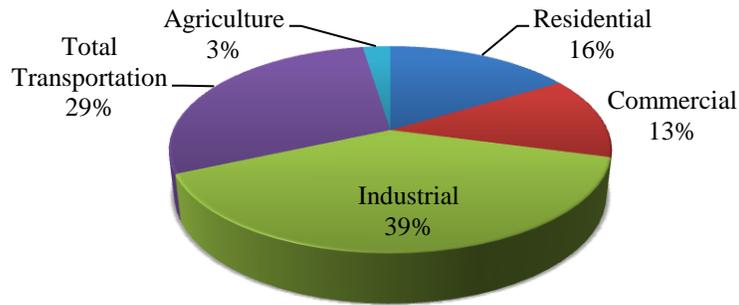
Figure 2: Energy Use by Sector in Canada (2007)[3]

In efforts to reduce the amount of fossil fuel energy uses to propel on road vehicles original equipment manufacturers (OEM's) have been focusing more attention on hybridizing and electrifying their fleets. As shown in Figure 3 in 2007 4% of automobiles sold in the United States were hybrids and the US EIA expects this to surpass 10% by 2015.
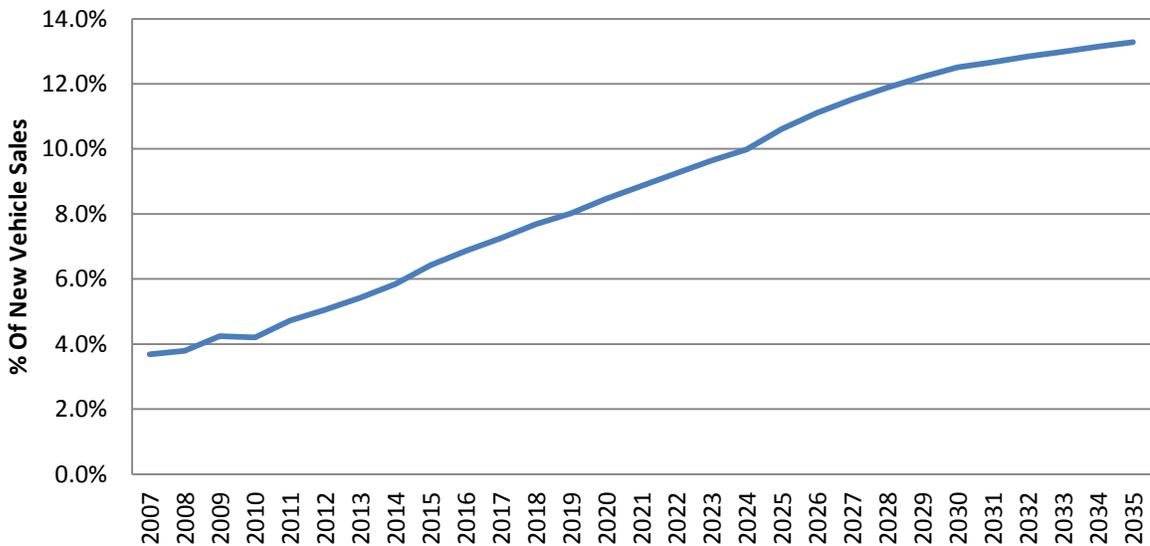
Figure 3: Actual and Forecasted Hybrid Vehicle Sales In the US (2007-2035)[4]

Another driving force for the development of vehicles with improved energy efficiency and reduced emissions are the national targets for reduced greenhouse gas emissions generated in

the transportation sector. Canada's 2020 target of 607 Mt is very aggressive and will cause all sectors producing emissions to adopt new advanced technologies to reduce their contribution (Figure 4). [5] With all driving forces considered the general direction of automakers is to electrify power trains to take advantage of new technologies such as batteries, fuel cells and other energy storage techniques that can be used to hybridize vehicles. In general, the short term focus is the massive adaptation of hybridized gasoline engines to take advantage of stop-start, regenerative braking and downsized engines while the long term will focus on removing gasoline internal combustion engines and switching to more efficient power converters such as fuel cells (Figure 5).
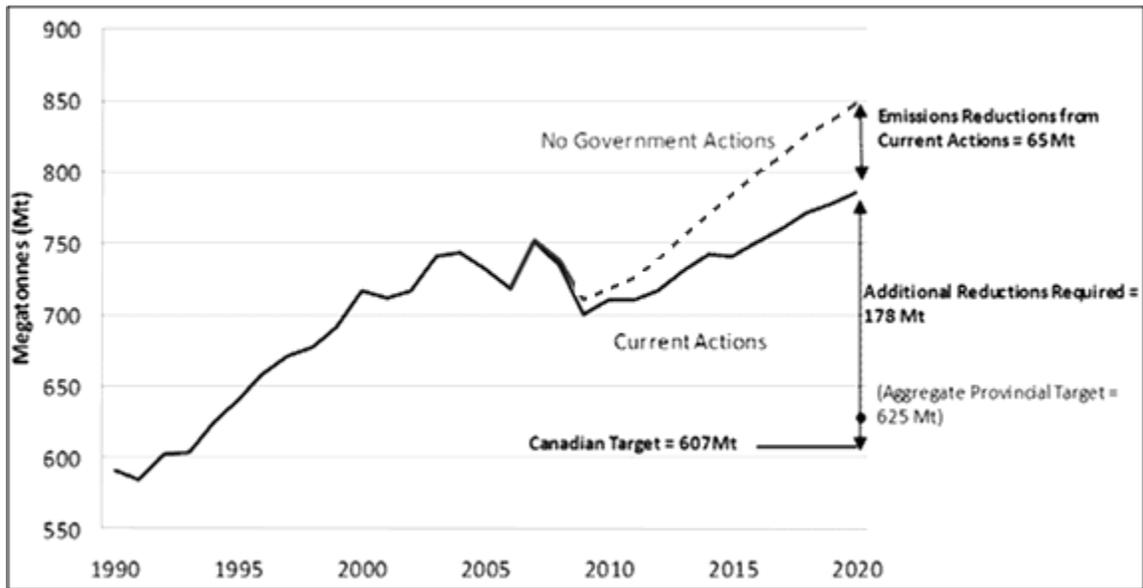
Figure 4: Scenarios of Canadian Emissions to 2020 (Mt C02)[5]
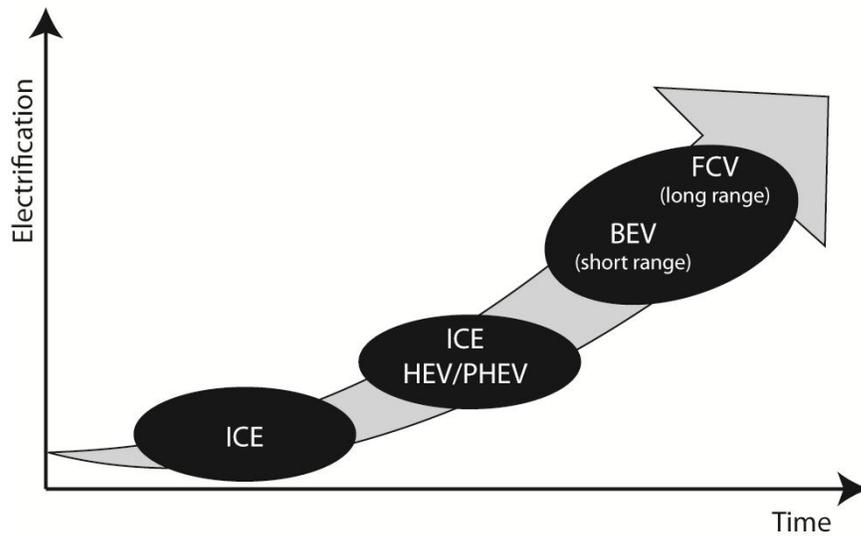
Figure 5: General Electrification Pathway

2.2 Pathways (common vehicle architectures, HEV, PHEV, EREV, FCV)

The ongoing developments of hybrid vehicles have led to a large number of designs exhibiting different advantages and disadvantages. Axen and Kurani [6] investigated consumer awareness of hybrid vehicles finding that the majority of people think that a typical hybrid vehicle available for purchase in the last decade can run on electricity from a wall outlet and still use gasoline. In fact, the vehicle with these characteristics does exist, however is commonly referred to as a *plug-in* hybrid electric vehicle (PHEV). The Chevrolet Volt and Toyota Prius Plug-In are commercially available examples of this capability. [7][8]

A paramount challenge that needs solving with advanced vehicle power trains is how to classify the immense number of vehicle architectures and configurations for the consumer to easily understand. Figure 6 summarizes some of the most common vehicle technologies available today. The diagram attempts to section the vehicle into its distinct categories. The first category is the fuel or energy input to the vehicle. Energy to propel the vehicle must come from a source that is either further converted onboard the vehicle or stored onboard and used directly to propel the vehicle. Currently gasoline and diesel fuels make up the majority

of road transportation energy use in Ontario with about 2% coming from alternative fuels and electricity.[3] Figure 7 shows this split over the past two decades. The second category is the onboard energy storage and conversion. The most common energy converter is the internal combustion engine which is either compression ignited or spark ignited depending on the fuel used and much less common but under prototype development is the fuel cell. Onboard energy storage can take many forms ranging from electrical storage such as batteries and ultra-capacitors to mechanical storage system like a flywheel or hydraulic (or pneumatic) accumulator. Finally the energy output of the vehicle is dependant not on its fuel or fuel conversion but related to the vehicle parameters, driver habits and driving conditions. The point to understand is for a vehicle with identical shape, mass and drive cycle the only way to improve the efficiency is to improve the energy conversion efficiency and use a fuel that enables more energy efficient conversion while minimizing harmful tailpipe and upstream generation of emissions. Different arrangements of the technologies presented below with various sizing and capacities have implications on the performance and functionality of the vehicle and can place inherent constraints on the system utility and consumer acceptance.

Energy (Fuel) Inputs	Converters	Energy Storage	Architecture	Energy Output (Demand)
Gasoline (RFG)	ICE (CI or SI)	Battery	Series	Aerodynamics and Road Drag
Diesel of Biodiesel	Fuel Cell	Ultra capacitors	Parallel	Vehicle Mass
Electricity	None	Flywheel	Series-Parallel	Drive Cycle
Hydrogen		Hydraulic		Driver Aggression
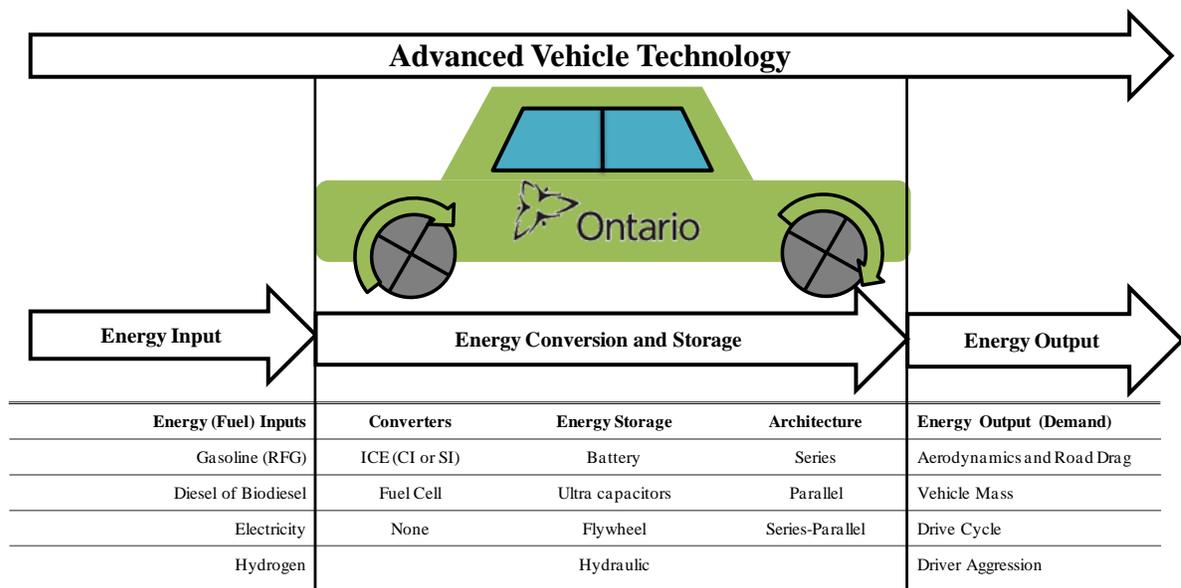
Figure 6: Advanced Vehicle Technologies
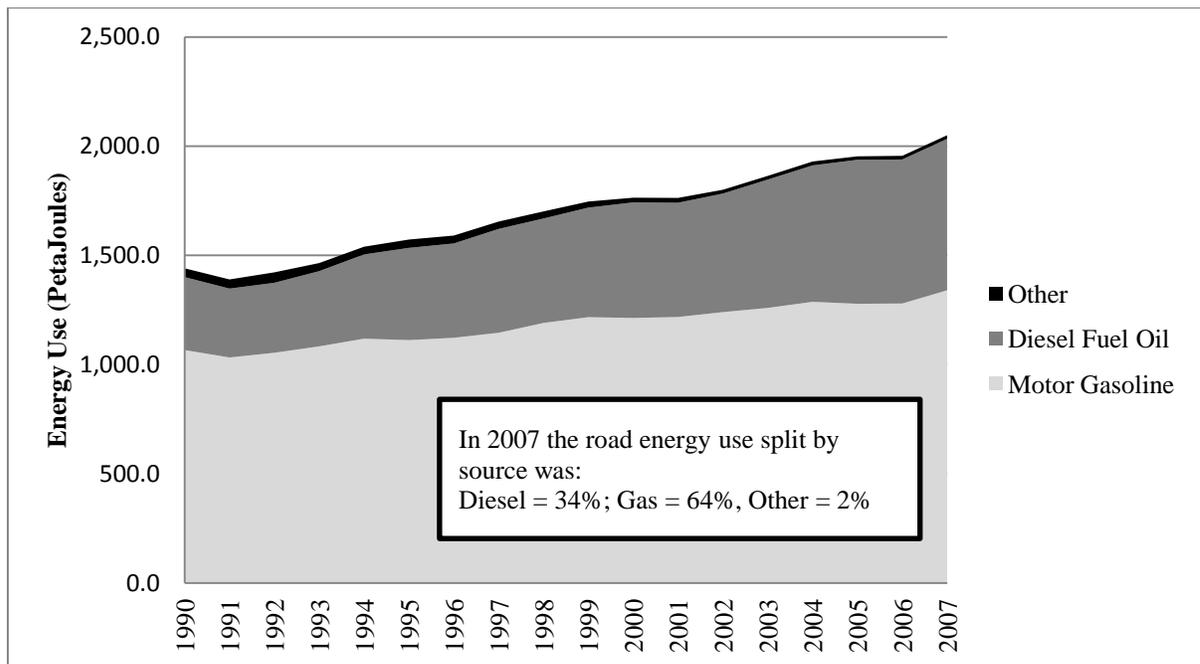
Figure 7: Road Transportation Use By Energy Source in Canada (from 1990 - 1007)[3]

The majority of hybrid vehicles that are commercially available today make use of the ICE and some form of energy storage, usually a battery or ultra-capacitor. There are many different types of hybrids, ranging from mild to heavy with varying degrees of advantages; the important features of common hybrid arrangements are summarized in Table 1. All hybrids commercially available as of September 2010 are Hybrid Electric Vehicles (HEV) with gasoline or diesel fuel as the only energy input. Later in 2010 the Chevrolet Volt, and Extended Range Electric Vehicle (EREV), and Toyota Prius, A Plug-in Hybrid Electric Vehicle (PHEV), will be the first hybrid vehicles to make use of energy from the electrical grid. In addition vehicles like the Nissan Leaf, a Battery Electric Vehicle (BEV), will only use electricity as input but will inevitably sacrifice vehicle range and convenience due to required charging schedules.

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Table 1: Advantages and Disadvantages of Common Hybrid Architectures

ADVANTAGES	DISADVANTAGES
Hybrid Electric Vehicles (HEV)	
• Downsized engines with the same or better vehicle performance • Engine stop/start at idle and (limited) all-electric operation • Does not always require a transmission • Enables regenerative braking • Electric launch and assist	• Vehicle cost may be higher compared to conventional vehicles • Some hybrids will exhibit little to no efficiency gains in highway driving situations, as there is no opportunity for recovering kinetic energy • Increased complexity and more components compared to conventional vehicles – likely that most power train maintenance will be done at the dealership, and may add weight to the vehicle decreasing overall vehicle efficiency
Plug-In Hybrid Electric Vehicles (PHEV)	
• In general, all PHEVs exhibit the same advantages as HEVs • Grid-connected battery enabling the displacement of gasoline and reduction of consumer operating costs (cost of electricity is less than gasoline) • The all electric range reduced urban air pollution, and in most cases (depending on the source of the grid electricity) reduces the well to wheel greenhouse gas emissions • Quiet all-electric operation (speed and power limited, although ICE may turn on under heavy acceleration or cold temperatures)	• More expensive vehicles (attributed to the large, high capacity plug-in battery) • Charging restrictions • Increased weight of the vehicle from the batteries decreases vehicle efficiency • Utility infrastructure to recharge the vehicle will be impacted
Extended-Range Electric Vehicle (E-REV)	
• Similar to PHEV except the vehicle exhibits all-electric operation under all conditions until the battery is depleted at which point the ICE turns on and acts as an HEV	• Battery and electric drive need to be sized to meet the full range of vehicle power demands (may increase cost and weight)

In general, not all hybrid vehicles will exhibit the same advantages and disadvantages above, but will vary depending whether they are mild (weak) hybrids or full (strong) hybrids. Discussion relating to the degree of hybridization can be found in the next section. Whether overall safety is a net advantage (e.g., lower emissions), disadvantage (e.g., high voltage battery), or unchanged is yet to be determined.

Although consumers are less interested in the fine details of powertain arrangements, the research community will pay close attention to the mechanical and electrical architectures in new vehicle designs. The layout can impact the vehicle performance, function and control complexity.

Classification of hybrid vehicles, regardless of fuel input and component size can be classified, first, by their topological architecture and, second, by their degree of hybridization or electric fraction. Today's consumers may be more concerned with the later since it will relate to vehicle functionality. As an example, the majority of vehicle consumers may not know why a car needs a transmission or even how it works, but recognizes the cars performance and fuel economy. In the same sense one may not care how new hybrid components are arranged, even though some configurations will offer benefits over others, but rather will only care to know the performance and operational modes. Modes such as ICE start-stop may be available on a weak or mild hybrid but all electric driving modes may be available on a stronger or full hybrid. The degree of hybridization will help define a spectrum of hybrids ranging from weak to strong. Consumers will need to weigh the costs against the benefits of such systems, as one already does when purchasing a conventional vehicle. Further classification of hybrids into charge sustaining, charge depleting, or blended strategy is necessary to distinguish between vehicles that may use net energy from the electrical grid or may only charge from power sources onboard the vehicle.

2.2.1 ICE Mechanical Series

In a series hybrid power train there is no direct mechanical path to the wheels. Typically an engine is coupled to a generator which produces electrical energy that can power an electric motor or charge a high voltage traction battery. In this architecture the battery is usually sized to meet peak acceleration demands while the engine can generate the continuous power required at the wheels. This architecture has the advantage that the engine can run at speeds independent of the wheels allowing the engine to be operated at its peak efficiency throughout a drive cycle. In contrast, because of the power conversions through a generator, into and out of a battery and then back through a motor the efficiency of the power train is reduced compared with direct mechanical coupling to the wheels [9].

Table 2: Advantages and Disadvantages of Series Hybrids [10]

Advantages	Disadvantages
• Engine can run at efficient operating speeds independent of wheels • Engine only needs to meet continuous power demands of vehicle • Does not require a transmission	• Electric motor must be sized for peak power of vehicle • Series energy loses from converting mechanical energy to electrical and back again • Increases mass since an electric motor and generator are required
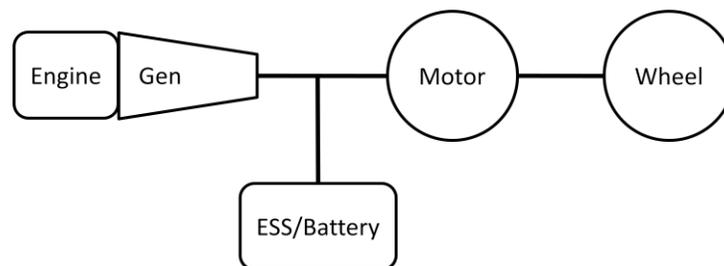
2.2.2 ICE Mechanical Parallel

Parallel hybrids have two independent mechanical paths to the wheels usually from an ICE and electric motor. The parallel hybrid requires a torque coupling to allow blending of the two power sources. Since this architecture can have a direct coupling to the wheels it can achieve a high efficiency conversion when the vehicle requires steady power draw. There are multiple levels of parallel hybrids ranging from mild to heavy hybrids. Mild hybrids such as a belted alternator starter allow for stop-start capabilities and lower levels of added electric power assist. Heavy hybrids can add much more traction power to the wheels at the cost of larger motors and energy storage [9][11].

Table 3: Advantages and Disadvantages of Parallel Hybrids[10]

Advantages	Disadvantages
• Can provide mechanical power to wheels avoiding the losses mentioned in series architectures • Only one electric machine is required and the sum of the ICE and electric machine can meet the peak power demand decreasing the size of the ICE and motor	• ICE cannot always operate at its most efficient operating point • A transmissions is required • Mechanical couplings may be more complicated
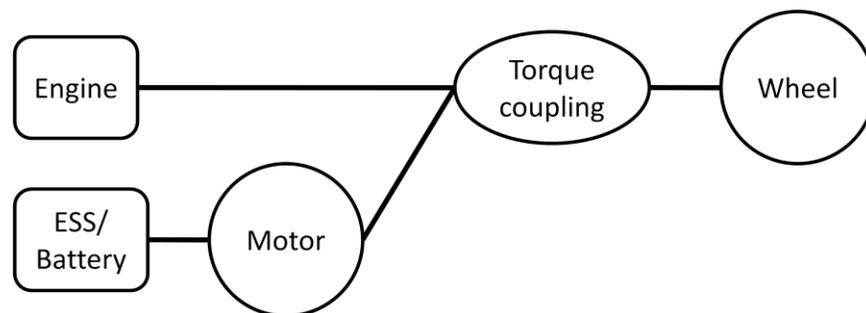
2.2.3 ICE Mechanical Series-Parallel

This setup combines the advantages of both series and parallel architectures by neatly blending torque from an electric motor, generator and engine, typically through an advanced planetary gear set. The disadvantage to this architecture is the added mass due to the more complex torque coupling and added generator in the series path [9].

Table 4: Advantages and Disadvantages of Series-Parallel Hybrids [10]

Advantages	Disadvantages
• Adapts the advantages of both series and parallel architectures • Electric motor does not need to be sized for the peak power of the vehicle as in a series architecture	• Increased control complexity • Increased number of components (transmissions, engine, motor and generator)

2.2.4 Degree of Hybridization

Hybrid vehicles of varying architectures are commonly classified as weak, mild, strong and full by media and the auto industry. The degree of hybridization in mechanical hybrid-electric vehicles is the ratio of peak electric motor power to the total power train power. Figure 8 shows the degree of hybridization and the associated operating modes.

$$Electric\ Fraction = \frac{peak\ elec.motor\ power}{total\ powertrain\ power}$$

Equation 1
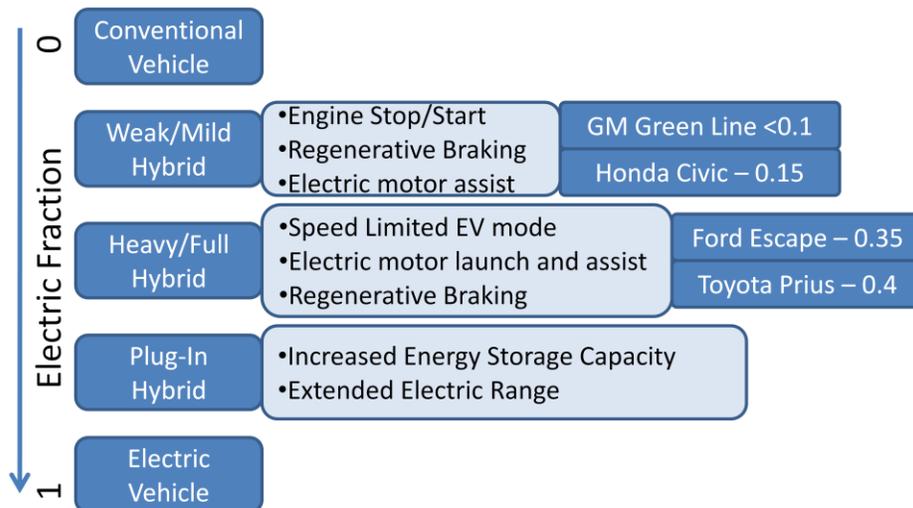
Figure 8: Degree of Hybridization (Electric Fraction)

2.3 Hydrogen Fuel Cell Vehicle Architectures

Fuels cells are electrochemical devices that convert chemical energy into electric energy and heat. Fuel cells may operate on various hydrocarbon based fuels however the most promising case for use in vehicles is the hydrogen fuel cell. In the automotive market polymer exchange membrane type stacks (PEM) powered by pure hydrogen are typically used. This technology is very efficient over a wide power range, easily refuelled, and produces zero harmful emissions (with water the only emission). Fuel cells are

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electrochemical devices and are not constrained to the Carnot efficiency that limits heat engines like the ICE. The maximum thermal efficiency of the hydrogen fuel cell is 83% (25 degrees Celsius) however more commonly found in practice are efficiencies from 40-60% for complete vehicle fuel cell systems. Take note that the fuel cell stack is the key component of a fuel cell system which also includes reactant handling (e.g. air compressors, hydrogen recirculation pumps), cooling systems, and power converters. The fuel cell's efficiency varies as the power changes due to activation, ohmic and concentration polarization losses in the cells (see Figure 9) [12]. References [13] and [14] note the characteristics of fuel cell stacks shown in Figure 10. The desired operating range of the example fuel cell system would then be located in the region of 10% to 50% of the maximum output power. The vehicle control strategy should avoid operating the fuel cell below 10% of its rated power since the efficiency is very poor because of the need to operate the air compressor in this range. This type of engine performance would serve well for vehicle loads that are typically modest but require peak power for short periods of time.
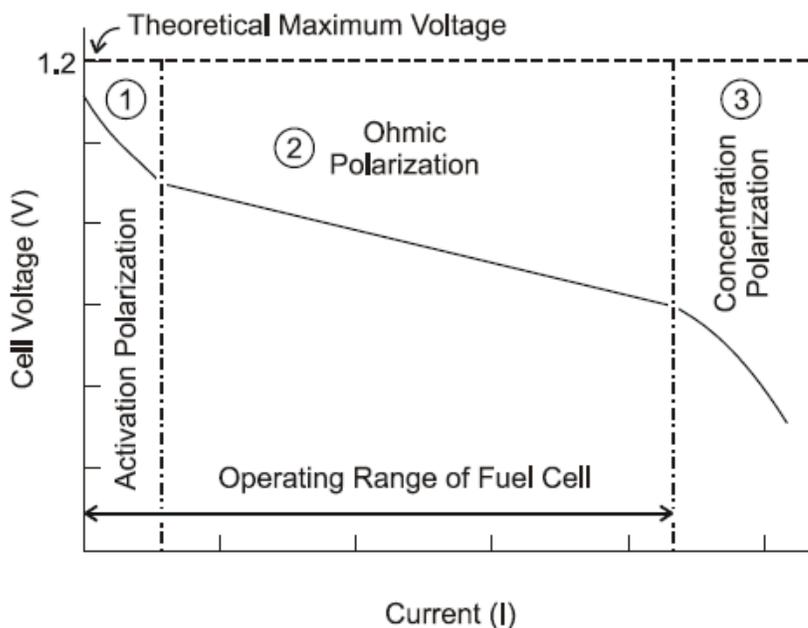
Figure 9: Losses in a typical Fuel Cell [12]
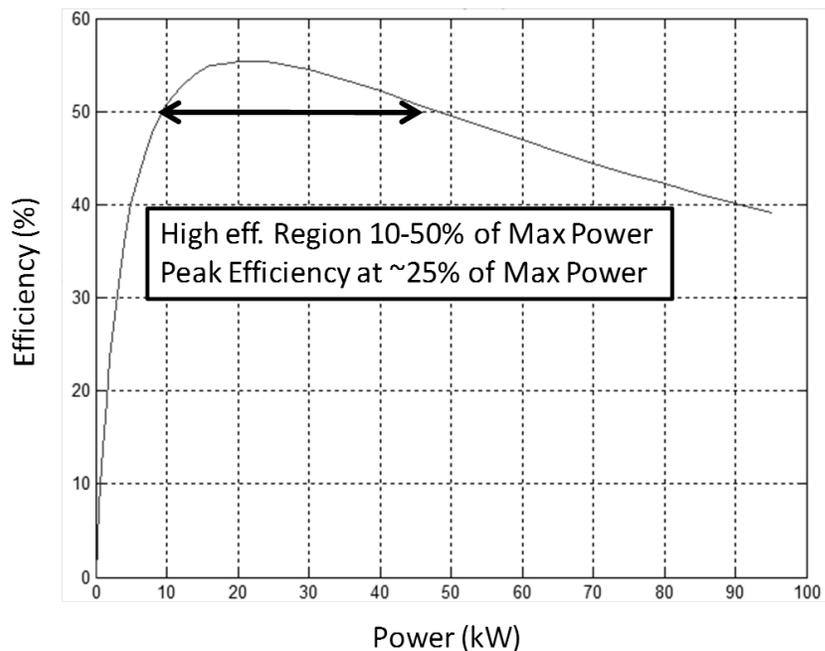
Figure 10: Fuel Cell System Efficiency [anonymous OEM system]

When considering a fuel cell only vehicle it parallels a conventional vehicle by replacing the ICE with a fuel cell and the transmission with an electric motor. As such a fuel cell powertrain is an all-electric powertrain. By hybridizing the fuel cell vehicle with some form of electrical energy storage one can further improve the vehicle efficiency by capturing additional energy from regenerative braking and can also take advantage of a downsized fuel cell with the battery providing additional power when required. The only fuel cell hybrid is of a series architecture closely emulating the mechanical ICE series architecture. The range of hydrogen fuelled vehicles is one of the greatest challenges associated with their development along with the challenge of a hydrogen infrastructure [15][16]. The US Department of Energy, through FreedomCAR, has set ambitious targets for all aspects of hydrogen storage shown in Table 5. These goals aim to improve the feasibility and practicality of hydrogen storage systems for use on board vehicles. The long term goals (2015) for mass and volume are nearly half of the current values and cost is expected to be one third.

Table 5: FreedomCAR Hydrogen Storage Targets [17]

Storage Parameter	2005	2010	2015
Gravimetric Capacity	1.5 kWh/kg 0.045 kg H2/kg	2.0 kWh/kg 0.060 kg H2/kg	3.0 kWh/kg 0.090 kg H2/kg
System Mass:	**111 kg**	**83 kg**	**55.6 kg**
Volumetric Capacity	1.2 kWh/L 0.036 kg H2/L	1.5 kWh/L 0.045 kg H2/L	2.7 kWh/L 0.081 kg H2/L
System Volume:	**139 L**	**111 L**	**62 L**
Storage System Cost	$ 6 /kWh	$4 /kWh	$2 kWh
System Cost:	**$1000**	**$666**	**$333**
Refuelling rate	0.5 kg H2/min	1.5 kg H2/min	2.0 kg H2/min
Refuelling time:	**10min**	**3.3 min**	**2.5 min**

Overall hydrogen as an energy carrier can be produced from multiple energy resources such as fossil fuels, nuclear, and renewables for multiple end-uses. This has led to the development of the *hydrogen economy* concept which concentrates on the study of the economic aspects associated with the production, distribution, and utilization of hydrogen in energy conversion systems. Hydrogen is a desirable long term energy vector because it can be stored and used to generate electricity, it can be produced from a diversified range of production pathways, it represents a secure energy supply, and when used in transportation applications it results in decreased urban pollution and GHG emissions. From the electrical grid management point of view, the use of hydrogen as an energy carrier is appealing in the context of energy storage impacts on competitive electricity markets, that is, enabling advantage to be taken of the significant price differences between peak and off-peak pricing hours (which may or may not necessarily coincide with peak and off-peak demand hours

For transportation purposes hydrogen can be burned in an ICE, however, this mode of operation will produce NO_x emissions, a primary and necessary ingredient to the soup that creates smog. Furthermore, there is a more efficiency alternative to the ICE when hydrogen

is used, and that is the fuel cell. For automotive applications a proton exchange membrane (PEM) type fuel cell is typically used as it has the best characteristics in terms of size, mass, and operating temperatures for automotive applications.

The transportation sector contributes significantly to GHG emissions in Canada, making up 22% of Canada's CO_2 emissions.[18] Canada's federal government has targeted a 60-70% reduction in GHG emissions, relative to 2006 levels, by 2050. [19] A fuel cell vehicle (FCV) is one of only two transportation technologies that can achieve this goal, the other being BEVs, however, BEVs are foreseen to continue to be challenged by limited range, limited durability, and long recharge times. FEVs can truly have zero emissions on a well-to-wheels basis when fuelled with hydrogen that has been produced using renewable energy. Even when fuel cells use hydrogen made from natural gas, the GHG reductions are over 50% as compared to today's ICE vehicles. While other technologies (for example, HEV, PHEV) will contribute to GHG reductions, the deepest cuts in fossil fuels use and GHG emissions come from the use of FCVs or BEVs. At high volumes, fuel cells offer the potential for the lowest life cycle costs of all zero-emission technologies, and hence are expected to be the superior long term solution (see Figure 5).

It is worth noting that an extended-range electric vehicle (E-REV) such as the Chevy Volt is in truth still an ICE PHEV but with very strong hybridization or electrification. FCVs too are also PHEVs and may be used as the primary powerplant or as the 'range extender.' That is, PHEV architectures are both the near and long term future for vehicle powertrains.

 It is expected that HEV, PHEVs, and E-REVs will be transitioning technologies as the hydrogen economy and associated technology and infrastructure is developed and prototyped Although this document focuses on the near term transition to PHEV vehicles there is a need to consider hydrogen as an important part of integrated energy systems in the long-term (that is, beyond 2020).

2.3.1 Fuel Cell Vehicle Topologies

With the introduction of the fuel cell into the hybrid vehicle the power electronics architecture becomes an important consideration in power train design. Table 6, Table 7, and Table 8 identify and summarize the advantages and disadvantages of three common electrical topologies for fuel cell vehicles. The DC/DC converters contained within the topologies are extremely important for the success of a fuel cell system. The DC/DC converter controls the current flow between high voltage busses with different voltages and ensures compliance and stability in the high voltage system. This will also allow components to be sized for power rather than the matching of voltages of the fuel cell, battery pack and electric motor. One should also consider that fuel cells and batteries degrade over time changing their operating voltage profiles and hence may become incompatible over time if they are directly coupled. DC/DC converters are the control point on the high voltage bus for either current or voltage and hence power flow [15].

Table 6: Series Fuel Cell, Unidirectional DC/DC

Advantages	Disadvantages
• High efficient energy path from battery to motor for increased "regen" efficiency and application for plug-in battery option • Simpler, lighter, cheaper and more efficient unidirectional dc/dc converter • Makes more sense for a charge depleting vehicle	• Efficiency loss for any power generated from fuel cell

Table 7: Series Fuel Cell, Bi-Directional DC/DC

Advantages	Disadvantages
• High efficient path from fuel cell to motor Advantages • Makes more sense for charge sustaining strategies and longer trips	• Sacrificed regenerative braking efficiency • Reduced efficiency for charge depleting strategy

Fuel Cell — Motor

DC/DC

ESS
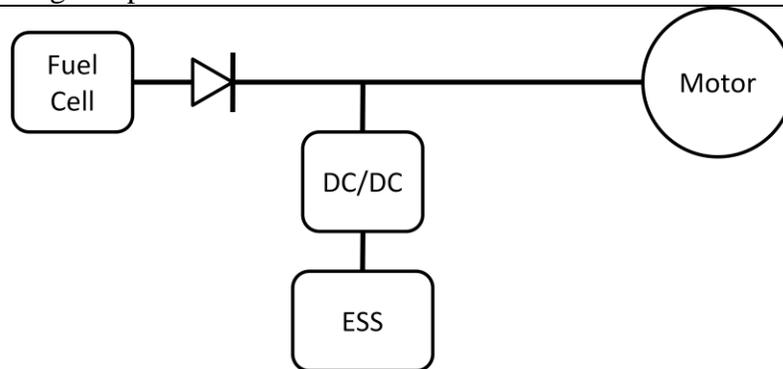
Table 8: Series Fuel Cell, directly coupled bus

Advantages	Disadvantages
• High efficient path between fuel cell, motor and energy storage • High regen efficiency (even more than battery) and capable of capturing more braking energy (higher charge currents)	• No control - Fuel cell can operate in inefficient power regions • Although theoretically possible, the degradation of power sources with time can lead voltage compatibility issues

Fuel Cell — Motor

ESS
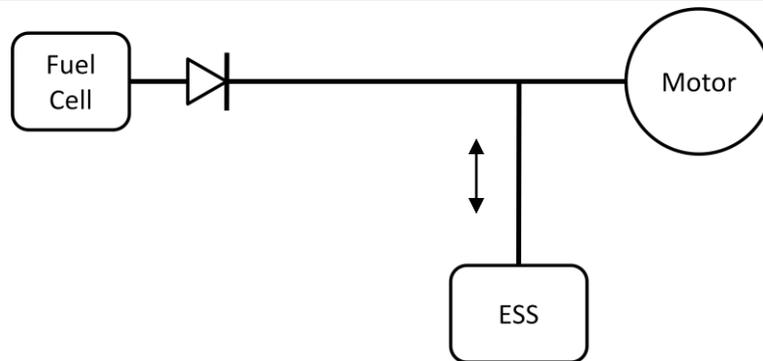
2.4 Battery-Based Energy Storage Systems

The key enabler of hybrid vehicle technologies is the on-board energy storage system (ESS) which augments the vehicle's primary power source. In some cases such as E-REVs, BEVs and fuel-cell vehicles (FCVs), the ESS may be the only power source to the wheels. Of current interest to the auto industry is the development of electricity energy carriers. One can store electric energy electrochemically in a battery, chemically as hydrogen, mechanically in a flywheel, and in electrostatic form via an ultra-capacitor. This section focuses on battery-based energy storage systems (ESSs).

In general, electric energy storage systems enable the following benefits for HEV and PHEV's:

- the ability to recapture the vehicle's kinetic energy through regenerative braking that would otherwise be lost in the conversion to heat from conventional mechanical braking;
- to meet peak power demands with a faster response time;
- to reduce the size, cost, and mass of the primary power source (engine downsizing); and
- in some cases the ESS can enable a control strategy where the primary power source (ICE or fuel cell) runs in a more efficient operating zone. In this situation the ESS acts like a buffer between the power demands of the vehicle and the power delivery of the primary energy source. With these two elements now asynchronous, the power source can operate in its most efficient range regardless of the current power demand, and any excess or deficit in energy production is handled by the ESS.

BEVs will only benefit from the first item in the above list, i.e., regenerative braking. There are a number of possible battery chemistries that can be used in an electrical energy storage system for PHEVs and BEVs. Presently, nickel metal hydride (Ni-MH) batteries are the most

commonly used technology in HEVs. However, analysts expect that lithium batteries will be best suited for future PHEV applications. This is due to expected design improvements that will yield significant energy and power density advantages while costs simultaneously decrease due to production quantities.

2.4.1 Critical Battery Metrics

When considering various batteries for automotive applications, there are several critical performance metrics: capacity, charge/discharge rate, energy and power density, operating voltage, self-discharge, cycle life, and state-of-charge. Battery capacity is the total amount of energy that the battery can store, usually stated in kilowatt-hours or watt-hours (kWh or Wh). This, combined with the efficiency of the various powertrain components, determines the driving range of the vehicle in "all-electric" mode, and consequently the extent to which a driver can displace fossil fuels during each trip.

Battery charge and discharge rates are the power acceptance and power delivery capability of a battery, usually stated in watts or kilowatts (W or kW). The charging rate and battery capacity can determine amount of time to fully charge a battery pack – this is usually limited by the on board charger. The rate at which a battery can supply energy to the electric motor(s) determines the vehicle's acceleration and grade climbing ability in "all-electric" mode.

Chemistry-specific metrics are the energy density and power density of the battery, usually stated in kWh/kg and kW/kg, respectively. These are the battery's energy capacity and discharge rate specifications divided by the battery mass. Higher values mean more performance delivered per kilogram of battery weight, leading to lighter and more energy-efficient vehicles.

Battery chemistry also determines the operating voltage of the battery, the "self-discharge" rate (the rate at which battery capacity is lost when idle), and the cycle life (number of times

the battery can be depleted and recharged). The cycle life is a function of the depth-of-discharge (DoD); typically, a larger DoD results in a lower overall cycle life.

Finally, the battery state-of-charge (SOC) refers to the amount of charge remaining in the battery (i.e. 100% SOC is fully charged, 50% SOC is half-charged, and 0% SOC is a fully depleted battery). Typically, a battery kept at a very high or very low SOC results in lower cycle life, although newer batteries are improving in this regard.

Table 9 compares the relevant specifications of some major battery chemistries: nickel metal hydride, lithium ion, and lead acid. Since the total weight of a PHEV battery is governed by its energy and power density, a specific chart called the Ragone plot is used to illustrate these key metrics. Figure 11 shows the higher energy and power densities of lithium cells that make them an attractive choice over Ni-MH and lead acid batteries [20]. The next section will elaborate further on the characteristics, benefits and downsides of lithium based batteries.

Table 9: Important data for Lead Acid, Ni-MH and lithium ion cells [20]

	Energy Density (Wh/kg)	Power Density (W/kg)	Voltage (V)	Self Discharge (%/Month)	Cycle Life @ 80% DoD	Cost ($/kWh)	Cost ($/kW)
Lead Acid	20 - 40	300	2.1	4 - 8	200	150	10
Ni-MH	40 - 60	500-1300	1.2	20	> 2500	500	20
Lithium Ion	100 - 200	800-3000	3.6	1 - 5	<2500	800	50 - 75
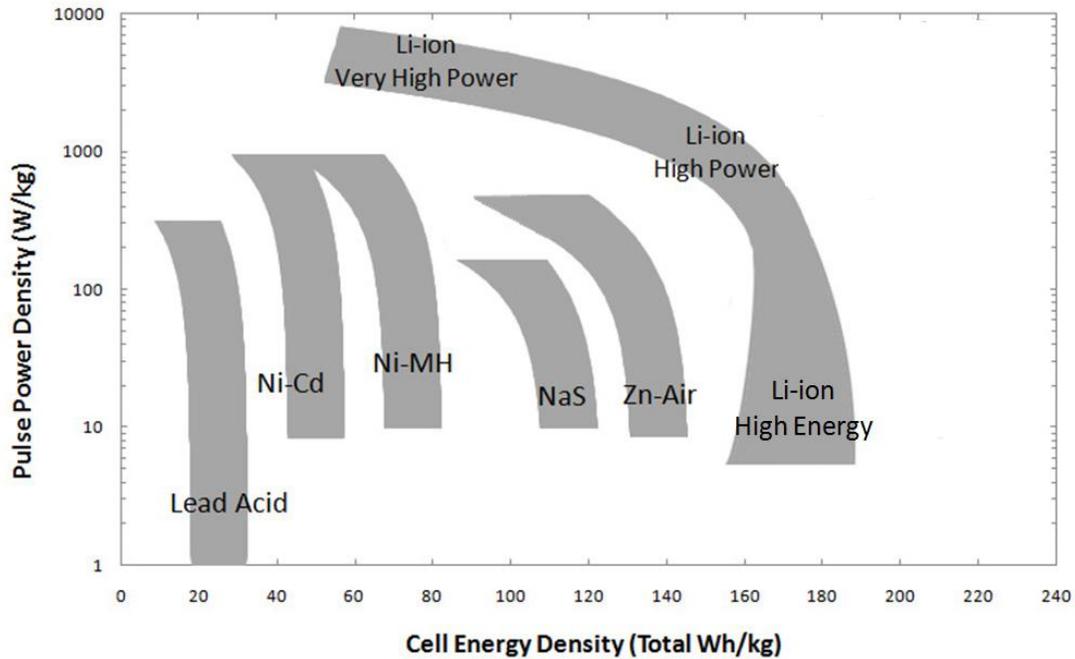
Figure 11: Ragone Plot of various ESS for PHEV applications [20]

2.4.2 Lithium-Based Batteries

Lithium based cells are widely seen as the cell that would work best for PEV applications. These cells are still in their infancy relative to some other cell chemistries but they show great promise for use in PEVs. There are three major types of lithium batteries: lithium metal, lithium ion, and lithium polymer.

Lithium metal batteries use a metallic lithium electrode. These electrodes have a very high energy density, mostly due to the lithium; however, this metal reacts with the organic electrolyte in the cell. The reaction forms a solid electrolyte interface and with extended use dendrites may form on the electrode surface and significantly affect battery life and efficiency. These types of cells typically show a short cycle life along with passivation effects (forms an oxide layer that does not conduct electricity) which severely limit their potential for use in PEVs.

Lithium-ion (Li-ion) batteries use an insertion compound as the electrode. A variety of different insertion compounds have been, the most important of which are titanium, iron phosphate, and manganese spinel technologies [21]. Each of these insertion compounds performs slightly differently, but they have very similar energy and power densities. Presently, lithium ion batteries are used in consumer applications with cobalt oxide as the insertion compound; however, the use of cobalt renders the cells prohibitively expensive for the scale required in PEVs. Table 9 shows the current cost of lithium ion cells, but this is predicted to drop to approximately $400/kWh in the medium term making them more affordable than Ni-MH cells [22]. The anodes of these cells are made from carbon structures that exhibit high specific capacity, low costs, and are easily cycled. Lithium ion batteries are safer than lithium metal batteries because of lithium metals instability.

Lithium polymer batteries use a solid polymeric electrolyte that also acts as a separator within the cell. These batteries can use the chemistry of lithium metal or lithium ion cells. Without the need for an electrolytic solution, the cell weight significantly decreases. Safety is also improves because there are no liquids that can leak from the cell. With a solid membrane, the geometry of the cell surface can be altered, allowing cells with different capacities to be easily created. However, the solid polymer electrolyte offers a significant downside in that it has a much lower conductivity than traditional liquid electrolytes. This lowered conductivity means that the membranes must be very thin to prevent large internal resistances, which serve to decrease the efficiency of the cell as well as increase the need for good thermal management.

At present there are still several challenges regarding lithium cell commercialization in vehicles, specifically their shelf life and cycle life. Due to lithium's tendency to react with the electrolyte, much energy is lost while the battery is in standby, a common occurrence in PHEVs. In addition, lithium cells require a very aggressive thermal management system because the cells can experience thermal runaway with improper control schemes. Safety concerns for lithium cells also exist due to these thermal management problems, as exampled

in media reports of laptop batteries catching fire. Also, at high temperatures the electrolyte will decompose into gaseous compounds. This requires that cells be equipped with venting capability or they may rupture, spilling the electrolyte and exposing the inner circuitry. There are additional concerns with lithium chemistries due to decreased conductivities at low temperatures, raising concerns regarding discharge power performance. Furthermore, the cells cannot be charged too aggressively or else lithium plating may occur leading to irreversible capacity loss; however, the possibility of plating can be removed through proper cell design.

Given current research lithium cells are the best candidate for future use in PEVs. Most lithium analysts foresee great drops in the cost of lithium cells as the manufacturing process is further developed. This is the greatest contributor to the high cost of lithium cells aside from the lithium itself, and with widespread adoption there may be lithium supply constraints.

With cost decreases projected in mind, lithium cells will eventually become less expensive than the Ni-MH cells. Further, owing to cell chemistry, researchers predict that lithium cells will provide the energy and power densities requisite for use in PEVs. In a general sense, basic research on lithium-ion batteries must focus both on developing new materials (electrode and electrolyte), developing new cell structures along with their thermal control. An important trend in lithium-ion battery development is the rising importance of nano-structured electrodes that offer the opportunity to improve discharge rate (power delivery) capabilities while maintaining high energy capacity.

2.5 Energy Storage State-of-Charge Management

One important categorization of hybrid vehicles is how the battery state-of-charge (SOC) is managed. A battery that on average maintains the same SOC by constantly being charged by the prime vehicle energy source (e.g., an ICE) or by regenerative braking is called "charge-sustaining" (CS). If the battery on average can deplete and use a net amount of energy from the electrical grid, i.e., a plug-in, it is called "charge-depleting" (CD). It should be noted that once a CD vehicle battery is depleted it can normally continue to operate as a CS hybrid vehicle. A summary of the operating modes of a hybrid vehicle is presented in Table 10 and further illustrated in Figure 12.
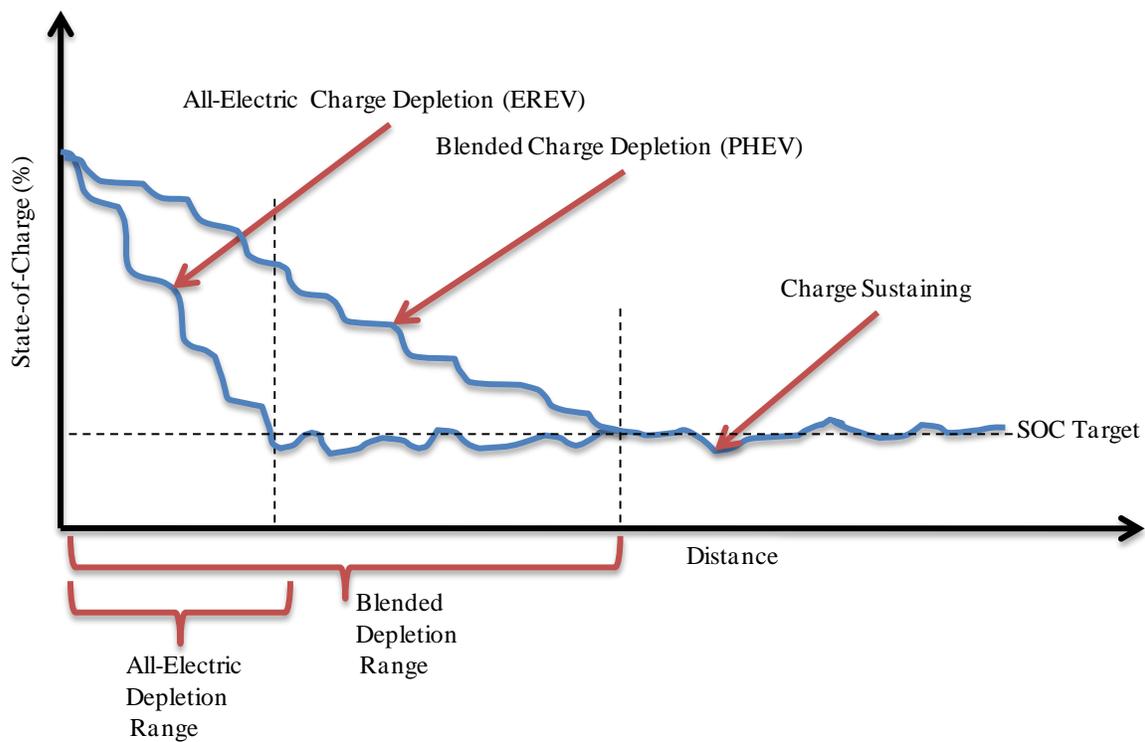
Figure 12: Charge Depleting Modes

Table 10: Hybrid Vehicle Operating Modes

Charge Sustaining (CS)	The vehicle will operate like a conventional hybrid in charge sustaining mode. In this mode, only gasoline is consumed. Regenerative braking can charge the battery when possible.	
Charge Depleting (CD)	The vehicle is using energy from the electrical grid. There are two possible CD modes. Once the "grid-charge" energy is expended, the vehicle enters CS mode.	
	Blended Mode	Vehicles can operate at lower speeds and/or with low loads on the electric motor without engine assist. However both battery and gasoline engine power are required to reach higher operational speeds or to meet higher loads (e.g., steep grade climbing). At these higher demands both electricity and gasoline will be consumed.
	All-Electric	Vehicles can operate at all speeds in electric mode until the battery reaches the SOC where CS mode begins. A vehicle that can operate in all-electric mode may also have the ability to operate in blended mode. In all-electric mode only electricity is used.

2.5.1 Charge Sustaining HEV

A charge sustaining (CS) HEV blends two or more power sources together by methods listed above in the various hybrid architectures. Over a drive cycle an HEV does not use a net amount of electrical energy and does not charge from the electrical grid; the only source of power for the energy storage system is the engine. The battery SOC is generally limited to a narrow window of 5-10% which leads to longer calendar life [23]. In other words the energy storage system maintains a steady state of charge (SOC), on average, but throughout a drive cycle the Energy Storage System (ESS) SOC may vary within a predefined range to meet acceleration demands or when recapturing energy through regenerative braking.

2.5.2 Charge Depleting HEV (PHEV, EREV)

Charge depleting (CD) hybrid vehicles have the ability to displace petroleum with the use of electricity. The battery SOC will fluctuate throughout a drive cycle but on average will deplete. A PHEV will initially operate in CD mode or a blended mode between ESS and the ICE. Typically a PHEV can only operate in a pure CD all-electric mode for to a limited speed at which point the engine will turn on and assist. Once the ESS SOC has reached a minimum set point the vehicle will enter CS mode and operate as a regular HEV. Thus the CD mode of operation has a limited range depending on the battery in use. Typically the all-electric range is represented by subscripts "xx" in the PHEVxx name.

A range extended electric vehicle design is only slightly different than the PHEV in that it is forced to charge deplete in all EV mode before the onboard ICE and generator turn are activated. This means the electric machine and battery must be sized to meet all of the vehicles technical specifications without assist from the ICE. The Chevrolet Volt is expected to be available during 2011; its battery, will provide an all-electric range of about 40 miles based on the UDDS cycle. When the battery has depleted from the maximum SOC of 80% down to 30% SOC it will enter into a charge sustaining series hybrid mode. Based on the 40 mile all electric range many drivers will be able to significantly reduce their gasoline consumption.

2.6 Fuel Economy Considerations for Plug-In Vehicles

2.6.1 Utility Factor

The 2001 National Household Transportation Survey (NHTS) conducted by the U.S. Department of Transportation provides general driving data for drivers. In particular it provides the cumulative frequency of distances driven per trip for the U.S. population, also known as the utility factor. In 2008 Argonne National Laboratory used the utility factor for calculating the fuel economy of a national fleet of PHEVs. The Canadian Vehicular Survey (CVS) is published quarterly by Statistics Canada and is the largest set of data on the general

Canadian driving population. Unfortunately only aggregate numbers, such as total kilometres driven by the Canadian population, are published. As such, obtaining a utility factor curve for the Canadian population is difficult using the CVS. However, smaller studies have been conducted which require participants to keep travel diaries. An example is the 2006 Transportation Tomorrow Survey, conducted by the Data Management Group at the University of Toronto, which surveyed drivers in the Greater Toronto Area. Figure 13 contains utility factors from two sources: the 2006 Transportation Tomorrow Survey for the Greater Toronto Area and the 2001 National Household Transportation Survey for the general U.S. population. The utility factor name comes from the intent to describe a vehicles practical usefulness. A vehicle that has a higher utility factor can drive further with its onboard energy storage and displace more gasoline.
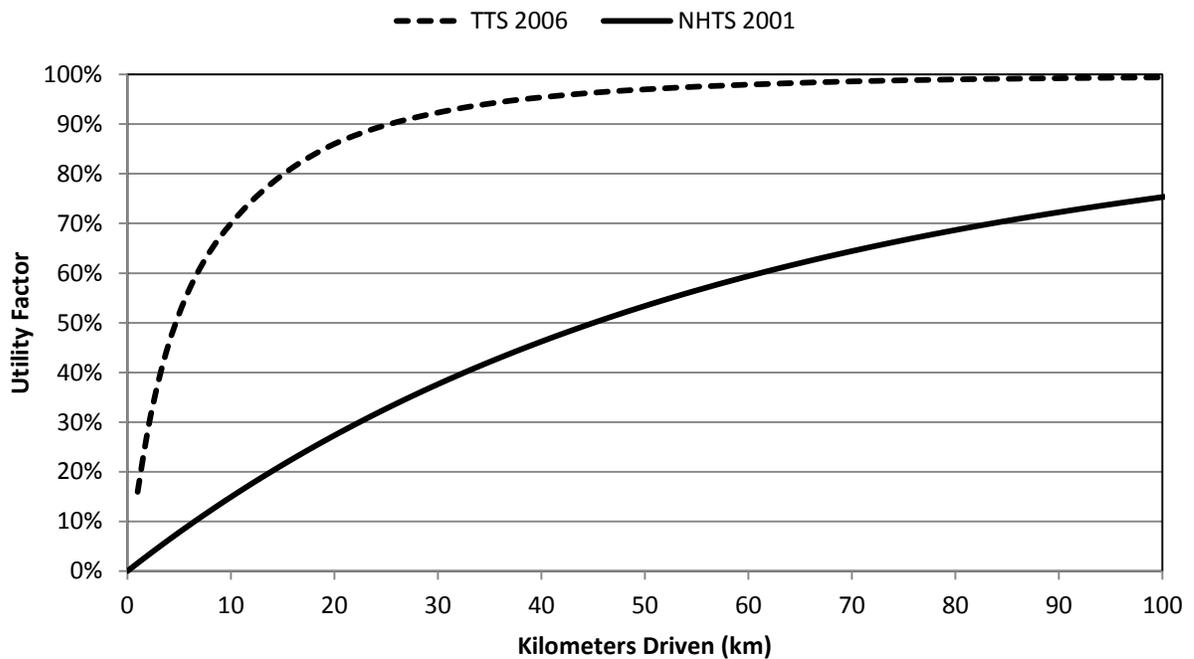
Figure 13: Utility factor indicates the fraction of total kilometres driven which use only electric energy [24][25][26]

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Based on Figure 13 and the NHTS data, a PHEV with a charge depletion range of 60 kilometres would expect to spend about 60% of the time travelling in charge depletion mode, i.e., all-electric mode, and 40% of the time in charge sustaining mode, i.e., gasoline ICE running mode. However, in sharp contrast, based on the TTS data, a PHEV with a charge depletion range of 60 km would expect to spend about 97 % of the time travelling in charge depletion mode and 3 % of the time in charge sustaining mode. The wide discrepancy between these two results clearly dictates that more work is needed to better understand the trip or utility factor profiles in different geographical and population areas. [24][25][26]

2.6.2 Fuel Consumptions Calculations Based on SAE J1711

Vehicles with multiple energy or fuel inputs create complications in measuring the traditional "mpg" or "L/100km" fuel economy or fuel consumption. Depending on the drive cycle a plug-in vehicle with a sufficiently long charge depleting range may use little to no fuel creating the misconception of abnormally high fuel consumption figures. To compensate for this the fuel consumption and emissions figures are measured during charge depleting and charge sustaining modes and then weighted based on the vehicles utility factor. Equation 2 , Equation 3 and Equation 4 give the utility factor weighted fuel economy, petroleum energy use and GHG emission results for plug-in, or charge depleting vehicles. Previously the calculation would merely use total fuel consumption over total distance travelled. SAE J1711 is expected to have a significant impact on the fuel economy ratings that automakers present to the public. Note for all electric vehicles the utility factor is set to 1 and for charge sustaining vehicles the utility factor is 0 reducing the equations to the standard form for conventional measurements of fuel economy. In addition the vehicles grid based electrical energy in Net electrical consumption is measured in AC kilowatt-hours and presented adjacent to the utility factor weighted fuel economy and emissions figures.

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$$FC_{UF}\left(\frac{l_{ge}}{100km}\right)=\left[\frac{\left(FC_{CD}*UF\right)}{Dist_{CD}}+\frac{\left(FC_{CS}*(1-UF)\right)}{Dist_{CS}}\right]*100 \qquad \textbf{Equation 2}$$

$$PEU_{UF}\left(\frac{Wh}{km}\right)=\left[\frac{\left(PEU_{CD}*UF\right)}{Dist_{CD}}+\frac{\left(PEU_{CS}*(1-UF)\right)}{Dist_{CS}}\right]/1000 \qquad \textbf{Equation 3}$$

$$GHG_{UF}\left(\frac{g}{km}\right)=\left[\frac{\left(GHG_{CD}*UF\right)}{Dist_{CD}}+\frac{\left(GHG_{CS}*(1-UF)\right)}{Dist_{CS}}\right] \qquad \textbf{Equation 4}$$

FC_{UF} Overall utility factor weighted fuel consumption (l/100km gasoline equivalent)

FC_{CD} Charge depleting fuel consumption (l/100km gasoline equivalent)

FC_{CS} Charge sustaining fuel consumption (l/100km gasoline equivalent)

$Dist_{CS}$ Charge sustaining distance travelled (km)

$Dist_{CD}$ Charge depleting distance travelled (km)

UF Utility factor based on charge depleting distance travelled (km)

PEU_{UF} Overall utility factor weighted petroleum energy use (Wh/km)

PEU_{CD} Charge depleting petroleum energy use (Wh/km)

PEU_{CS} Charge sustaining petroleum energy use (Wh/km)

GHG_{UF} Cumulative utility factor weighted green house gas emissions (g/km)

GHG_{CD} Charge depleting green house gas emissions (g/km)

GHG_{CS} Charge sustaining green house gas emissions (g/km)

2.7 Modern Controls in Advanced Vehicles

Sciarreta and Guzzella summarize well the control requirements and optimization potential for hybrid and plug-in hybrid vehicles. A control function that must be met by hybrid vehicles is that the demand must be met by a combination of power from the motor and engine. Additional algorithms are required to charge the battery from the engine and, at times, to satisfy the additional electrical loads in the system. As with conventional vehicles

there are engine controllers that supervise the fuel injection, throttle control, spark timing and other engine actuators. Hybrid vehicles have additional systems such as battery controllers, or commonly referred to as battery management systems (BMS), and motor controllers that all manage the closed loop control systems respective to their system boundaries. The BMS also plays the critical role of balancing the voltage of the cells within the battery pack (typically 200-400 cells). A relatively new control system boundary with hybrid, electric and fuel cell vehicles is what is sometimes referred to as supervisory control, hybrid control strategy or energy management of the vehicle. These control systems, and usually separate controllers that manage the energy flows in the system which include current control form sources, torque control form electric machines, thermal supervision in the system and additional safety strategies. With conventional vehicles there are zero degrees of freedom in respect to power, meaning all of the energy required to propel the vehicle must come from fuel energy. With hybrid vehicles an engine can often operate independent of the vehicle pedal positions, speed and gear to allow for optimization of fuel efficiency depending on the power split between the primary and secondary energy source. [27]
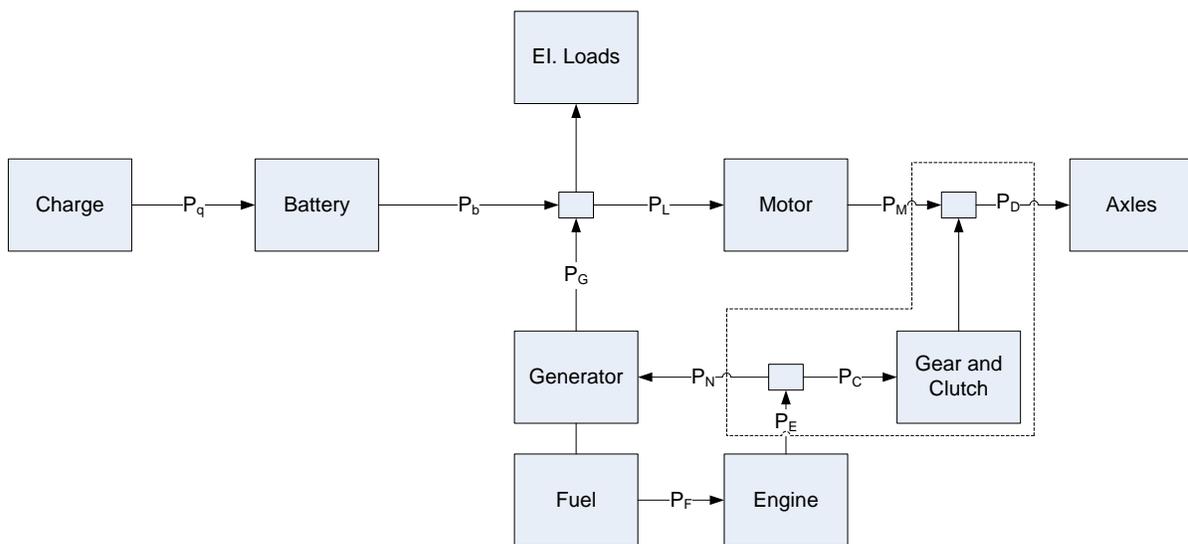
Figure 14: Energy flow of general hybrid powertrain. The dashed block can be physically realized with a planetary gear set [27]

In general the primary function of the hybrid control strategy is to control the energy, power and torque flows in the system while minimizing the costs associated with running the components. There is often a balance between minimizing fuel economy, emissions and performance. In addition the controller must stabilize or maintain the energy storage system's state of charge which is defined as:

$$SOC(t) = SOC(t_0) + \frac{1}{Q_{max}} \int I(t)dt$$

Equation 5

$$where: \ SOC(t_0) = \frac{Q(t_0)}{Q_{max}}$$

SOC - State of charge

t_0 - Initial time

Q - Capacity (Ah)

$I(t)$ - Current (A)

There are many more involved calculations to determine the state of charge for an energy storage system especially over time for a real-time control system. Furthermore, most storage systems are expected to sit idle for many hours or even days where the battery SOC is expected to change, however, this definition is expected to serve well for simulation and discussion purposes. For a charge sustaining hybrid the constraint on the system is to maintain an SOC over the cycle. It is reasonable for the SOC to fluctuate above and below a set target point but on average the SOC should be as close to net zero depletion or consumption as possible.

When charge sustaining, the controller may allow the SOC to fluctuate between a low and high set point such as 50% - 70%. This allows the system to stay in a given mode like all electric at low speeds, or heavy acceleration and let the battery be restored later with the prime energy source.

2.7.1 Rule-Based Control

Rule-based control systems in hybrid vehicles make decisions when specific criteria are met in order to satisfy the driver demand, electrical loads, component operational requirements and especially the energy storage charge management. These rules and conditions are usually based on engineering intuition of component performance and component efficiencies or informed based on offline simulation. Rule based control systems are easily implemented in a real time control system environment, like a vehicle, however will often result in less than optimal, but functional solutions.[28]

A form of simple rule-based control is often referred to as thermostat control. In an internal combustion engine series electric hybrid the objective of thermostatic control is to use the battery primarily to satisfy the vehicle power demand and turn the engine on to charge the battery at its most efficient operating point. A slightly modified thermostat control strategy was investigated by Jalil et al.[29] The basic rules in Table 11 were used to maintain the battery SOC and satisfy the driver power demand. The basic thermostat control normally allowed the engine to turn on at a certain power set point while charging the battery, however with the modified strategy the generator set can provide power through an efficient operating zone ranging from a low power limit to a high power limit. Above this high range the engine power is limited and any additional power demand must be satisfied by the combination of the generator and battery. This strategy results in less charging and discharging of the battery which improves the overall vehicle fuel economy.

Table 11: Thermostatic rule-based control [29]

IF	THEN
Lower SOC limit reached	• Engine/Gen is ON • $P_{gen} = \max(P_{optimal}, P_{demand})$ • $P_{batt} = P_{demand} - P_{gen}$

Upper SOC limit is reached	Idle Engine/Gen if ($P_{demand} < P_{min}$)
	    • $P_{gen} = 0$
	    • $P_{batt} = P_{demand}$
	Engine/Gen ON if ($P_{min} < P_{demand} < P_{max}$)
	    • $P_{gen} = P_{demand}$;
	    • $P_{batt} = 0$;
	Engine/Gen ON if ($P_{demand} > P_{max}$)
	    • $P_{gen} = P_{max}$
	    • $P_{batt} = P_{demand} - P_{gen}$

The strategy in general tries to operate the engine in a load levelling condition, meaning that the load on the engine should be relatively constant favouring operation at its most efficient point and avoiding transient operation when possible. Figure 15 and Figure 16 show the power and SOC profiles during a common drive cycle to illustrate the saw tooth charging typical of the thermostatic control strategy. This strategy is in contrast to a load following application where the engine would generally follow the power demand more closely. The load following strategy is especially common in parallel or series-parallel hybrids such as the Toyota Prius or Honda Civic hybrids that are commercially available. Note that many more rules are employed for the supervisory control of hybrid vehicles and it is overwhelming to list them all. For example another rule may be the vehicle speed and power demand combination that will allow all electric driving of the vehicle or the minimum vehicle speed that will permit regenerative braking energy recovery during vehicle deceleration.
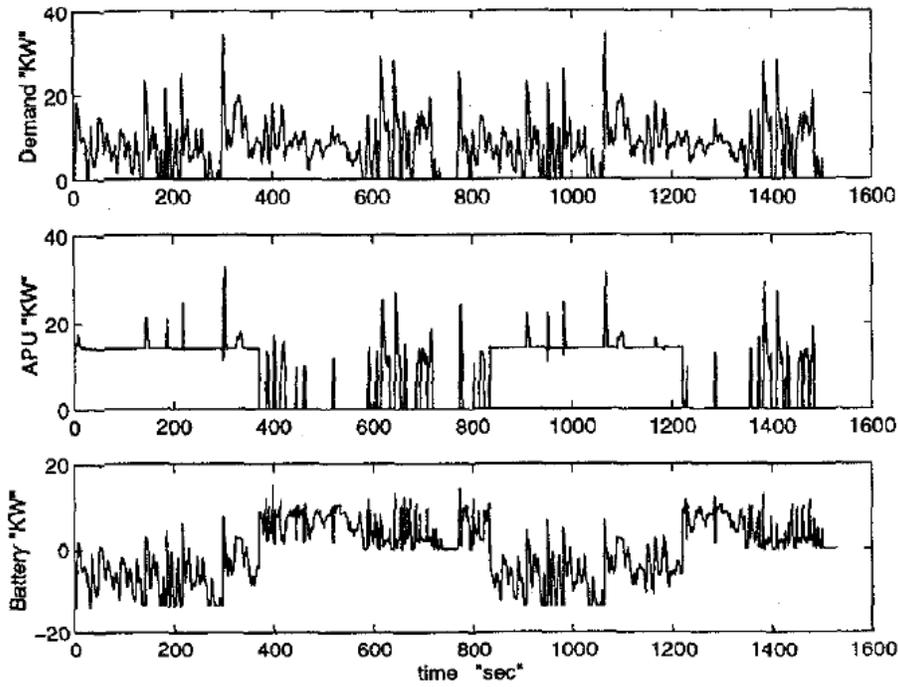
Figure 15: Power profiles during rule-based control of series hybrid [29]
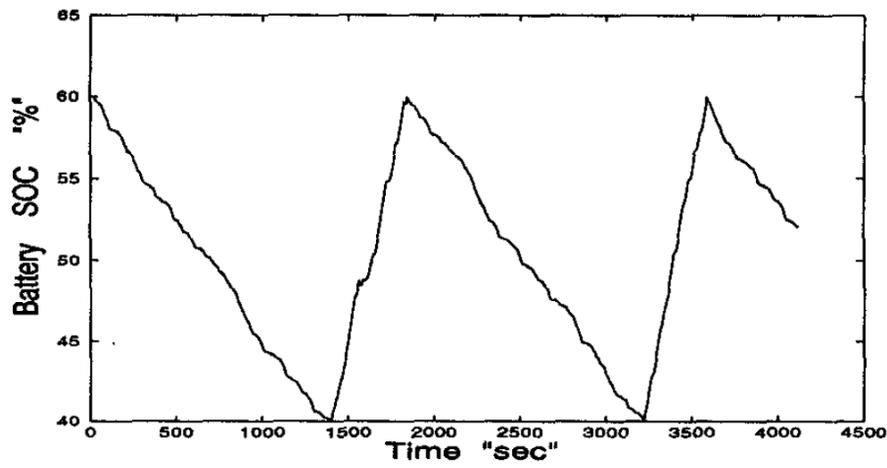
Figure 16: SOC profile during rule-based control of a series hybrid [29]

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2.7.2 Optimized Control

It is important to note that the most optimal solution for energy management systems can only be realized with an a priori knowledge of the drive cycle. Often when evaluating intuition based control systems the offline stochastically partitioned and globally optimized solution with knowledge of the drive cycle is used as a baseline comparison for evaluating real time control strategies. In addition results from dynamic programming can influence intuition based rules in real time strategies, especially when component efficiencies are inherently linked based on the state of system components. For example the electric motor efficiency may depend strongly on the voltage of the system which may be defined by a primary energy source such as a battery or fuel cell. Lin et al investigated the differences between a rule based control strategy and stochastic dynamic programming (SDP) optimization results in the energy management of a fuel cell hybrid electric vehicle. Table 12 shows that over most drive cycles the improvement ranges from 1-8 % with the best results in more demanding and transient drive cycles. [30]

Table 12: Fuel Consumption Comparison [30]

Driving Cycles	Rule-based control (g/km)	SDP control (g/km)	Improvement (%)
UDDS	9.33	8.86	5
LA92	12.64	12.14	4
HWFET	10.82	10.69	1.2
SC03	10.27	9.61	6.4
US06	18.79	18.09	3.7
NYCC	12.34	11.33	8.2

Other techniques that can be used to improve the knowledge of the upcoming drive cycle may include:

- Predictive Control;
- Analytical Optimization Methods;
- Past Driving Conditions;
- Past and Present Driving Conditions; and
- Past, Present, and Future Driving Conditions.

2.8 Controls Development and Model Based Design Process

One ongoing challenge in the automotive development is the processes surrounding development for robust production software controls in vehicles. Model based design can integrate closely into traditional software development cycles to help minimize software errors and unnecessary iterations and software releases. The following controls development process can be used as a model for required vehicle software driven by the primary Vehicle Technical Specifications (VTS).

2.8.1 General Control Development Plan

As typical in software development, well designed vehicle controls follows the v-diagram for software development and validation shown in Figure 17.
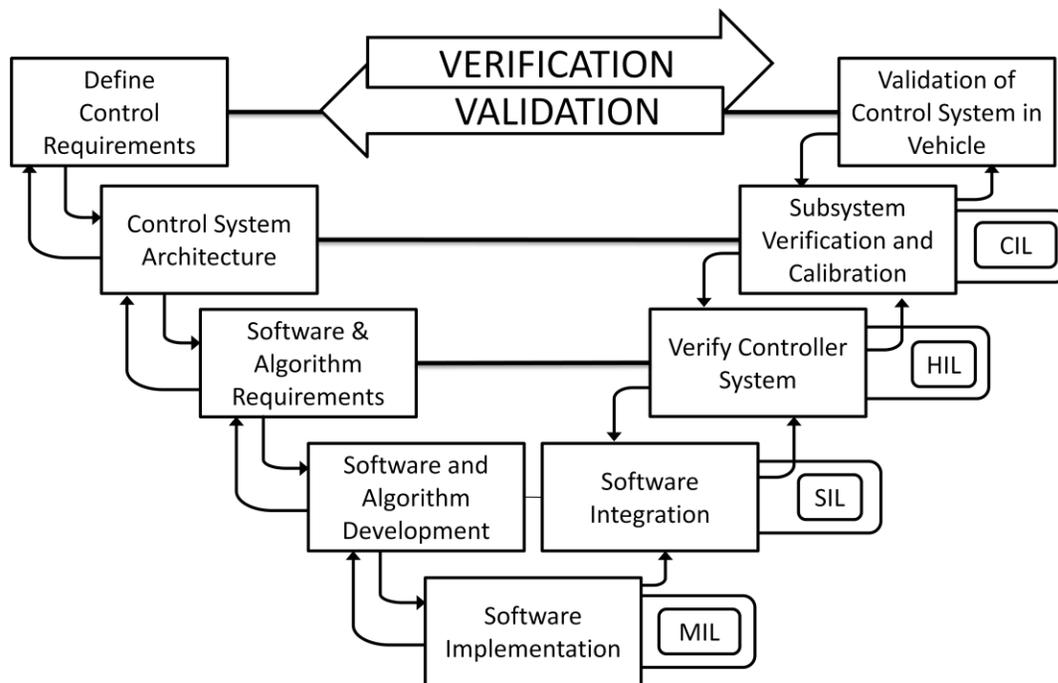
Figure 17: V-Diagram for Controls Development

2.8.2 Control Requirements

A plan to introduce new control requirements is essential to producing a safe and refined solution to meet control objectives and overall vehicle technical specifications. High level control functions are identified during the control requirements phase. For example, the electronic traction system will require a torque request. The driver demand will be converted into a torque request based on the accelerator pedal, brake pedal and available power. The hybrid control strategy will then determine how much power can be output from the fuel cell and energy storage system to meet the power demand.

2.8.3 Control System Architecture

After the high level control functions are identified, the necessary controller inputs and outputs will be defined in order to select an appropriate module to meet the control requirements. At this point the controller communications network should be designed before software development begins.

2.8.4 Software Requirements

Software requirements are based on high level control requirements and ultimately the desired vehicle functionality. At this point the control architecture should be modified based on any incompatibilities with the software requirements. For example, a requirement for the hybrid control strategy may be to split the available power between the fuel cell and energy storage system while maximizing efficiency and minimizing powertrain degradation.

2.8.5 Software and Algorithm Development

Software development attempts to achieve the software requirements at an algorithm level. At this point there may be minimal code generated and development of more high level control theory. For example to meet the software requirement of maximizing efficiency and minimizing powertrain degradation a cost function algorithm may be required to meet the objectives.

2.8.6 Software Implementation (Model in the Loop – MIL)

The algorithms must be transferred into code that may eventually be tested and loaded to a real time target. PSAT is an extremely useful for control strategy development and implementation. PSAT provides typical hybrid control strategies that users are allowed to modify to suit a particular application, such as load following or load leveling HEV. PSAT is essentially a GUI interface for MATLAB/Simulink and all control algorithms, component models and parameters are designed into Simulink models and then executed. PSAT models do not run in real time and the I/O signals to each component plant model are not necessarily the same signals that are used in the real component in the vehicle. PSAT is a practical choice for component selection and MIL development since EcoCAR teams are provided with in depth training for both PSAT and MATLAB/Simulink. In addition plant models for engines, transmissions, and vehicles are provided by Argonne as PSAT models for development over the course of EcoCAR.

2.8.7 Software Integration (Software in the Loop – SIL)

The next stage of control strategy development is the transition from PSAT development to SIL testing. With the aid of The MathWorks Real-Time Workshop a control loop for the entire vehicle can be run in real time on a desktop computer. The plant models used in the SIL simulation are I/O based to emulate the signals present in the vehicle. In MIL, continuous data for all variables is available all the time within PSAT. With SIL one can introduce the actual refresh rates of individual components which helps identify lags, hiccups and compatibility issues. There is also a transition from the continuous time domain into the discrete time domain. The powertrain controller, actuators, sensors, driver and vehicle plant models will be kept as separate blocks to ease the transition to controller and component verification. The key point here is that the actual control code can be separated into a separate compliable model that would easily be flashed to a actual microcontroller or used in the SIL testing model.

2.8.8 Verify Controller System (Hardware in the Loop-HIL)

HIL simulation separates the vehicle controller and plant models to unique hardware and connects them by a wiring harness that could be used in the vehicle. The vehicle controller sends actuation signals to the simulator and the simulator provides feedback signals to the controller based on plant model response. HIL testing can save a great deal of time and money with regards to control strategy development. It allows testing of control algorithms and controls hardware without requiring a prototype vehicle. HIL can lead to a safer prototype vehicle with early identification of communication problems or unsafe torque requests that would otherwise not be identified until vehicle deployment. HIL testing can automate fault insertion and emulate signal EMI to identify issues before testing at a vehicle level.

2.8.9 Subsystem Verification and Calibration (Component in the Loop - CIL)

Component in the loop replaces the plant models running on the simulator with the actual component hardware. CIL allows for more accurate simulations and increased confidence, since questionability of the plant model is removed from the simulation. The scale of CIL can range from a single component to the entire powertrain without the vehicle body. These simulations will be extremely close to the actual vehicle state since the plant models are replaced by the real world performance of the components. CIL testing can help refine and validate component plate models for use in MIL, SIL, and HIL testing.

2.8.10 Validation of Control System in Vehicle

Initial control system calibration can begin at the HIL testing stage. Although calibration at the HIL may not be identical to calibration at vehicle testing stage they will be in the same range and serve as a reasonable starting point for rollout to the actual vehicle. Once the control system is implemented at a vehicle level the calibration parameters can be tweaked to meet required output. During development one should leave parameters associated with

driver feel open for calibration. It is important to save and document working calibrations so that future code changes can start from a known working calibration.

Chapter 3
Vehicle Architecture of Study

In the first year of the EcoCAR challenge, UWAFT completed an in depth analysis comparing the various fuels pathways and topological vehicle architectures on a well to wheel basis. An array of criteria was used in the comparison that coincides with the EcoCAR prime objectives of improved energy conversion efficiency, reduced emissions and maintained consumer acceptability. The assumptions and factors used in the calculations for comparison are given in Figure 18.

Well to Pump (upstream or production use)					
WTP Factor	E10	E85	B20	H2	Elec.
GHG (g/kWh$_f$)	63.33	1.57	1.99	397.5	699.18
PEU (kWh$_p$/kWh$_f$)	0.931	0.0832	0.0642	0.0147	0.0785

Pump to Wheel (downstream or vehicle use)					
Vehicle Use	E10	E85	B20	H2	Elec.
Fuel Consumption (kWh$_f$/km) (GREET)	0.91	0.85	0.76	0.39	0.259
Tailpipe GHG emissions (g/km)	237.6	217.7	204.3	0	0
% Petroleum in Fuel	0.90	0.15	0.80	0	0

Figure 18: Assumptions and factors used for WTW calculations

Equation 6 and Equation 7 show the method used to calculate the combined well-to-pump and pump-to-wheel green house gas emissions and petroleum use for comparison.

$$GHG_{WTW} = \left(WTP_{factor}\right)\left(FuelUsed\right) + TailpipeEmissions \quad \left[\frac{g}{km}\right]$$

Equation 6

$$PEU_{WTW} = \left(WTP_{factor}\right)\left(FuelUsed\right) + \left(\%Petrol\right)\left(FuelUsed\right) \quad \left[\frac{kWh}{km}\right]$$

Equation 7

Figure 19 and Figure 20 show the final comparison of fuel pathways considering well-to-wheel greenhouse gas emissions and petroleum energy use.

WTW Green House Gas Emissions (g/km)
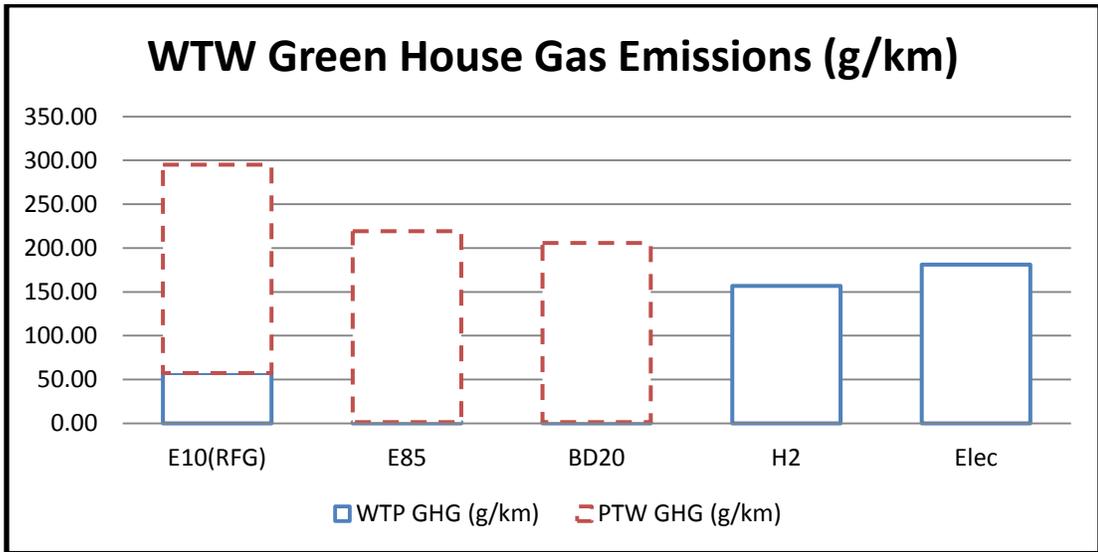
Figure 19: Well-to-wheel Green House Gas Emissions

WTW Petroleum Energy Use (kWh/km)
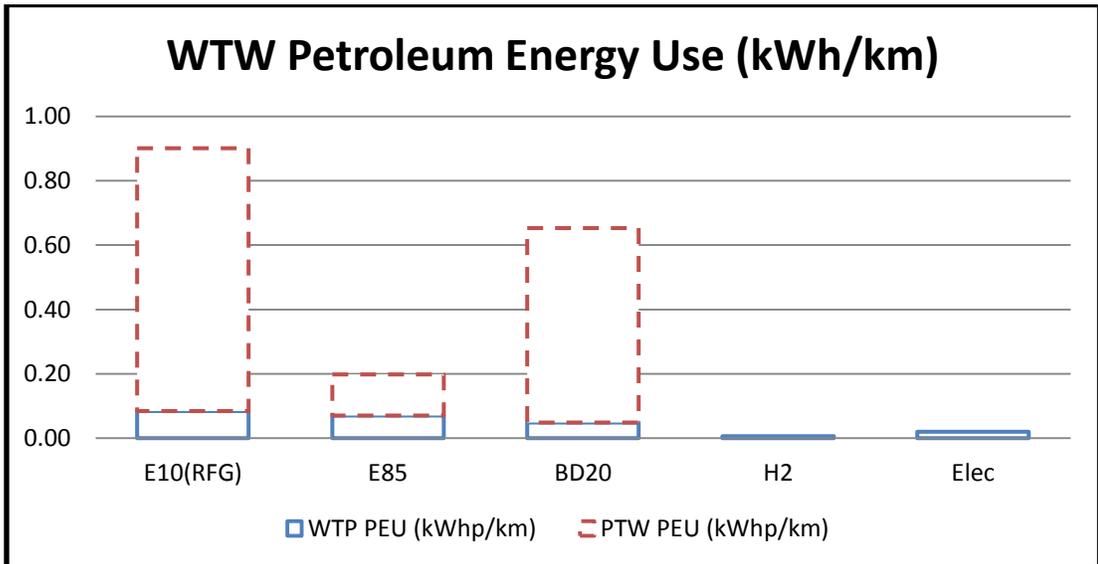
Figure 20: Well-to-wheel Petroleum Energy Use

In general one can conclude that both hydrogen and electricity pathways are favourable in the long term compared with liquid fuels on a well-to-wheel basis. The well-to-pump factors above are a combined average based on the population split in the United States and Canada (13% Canada and 87% United States). It is expected that electrical pathways are even more desirable in Provinces like Ontario with a large renewable and clean energy sources, compared with coal generation for example. It is also noteworthy that the hydrogen production is assumed to be generated from natural gas. The results, especially relating to hydrogen and electricity, can be expected to change significantly depending on the process. However, for the purposes of the EcoCAR competition the decisions made are based on the data presented. With this in mind, the team made a decision to develop a fuel cell plug-in hybrid electric vehicle (FC-PHEV). A resulting downside to selecting this architecture is that many of the desired component sizes and ratings were not available and it should become apparent through review this document that there is further potential for optimization of the powertrain sizing.

3.1 Fuel Cell Vehicle Topology

While there are multiple fuel cell vehicle topologies presented in the literature, many decisions were made based on restrictions of certain components. A unidirectional DCDC converter could be used but would require disassembly of the power electronics needed for the fuel cell propulsion system and therefore it was advised to proceed with a bi-directional DCDC topology as presented in Figure 21. This particular arrangement of components allows for a very high efficiency path from the fuel cell to the electric motors which will be especially noticeable for highway driving or constant load applications. The high voltage battery may be charged form the electrical grid thus allowing a charge depleting vehicle operating mode and a limited all-electric range. Implementing both a front and rear traction system was proposed because of the opportunity for motor efficiency gains by splitting power, the vehicle performance improvements (i.e. all-wheel-drive), and the ability to have vehicle functionality if one traction system were to fail.
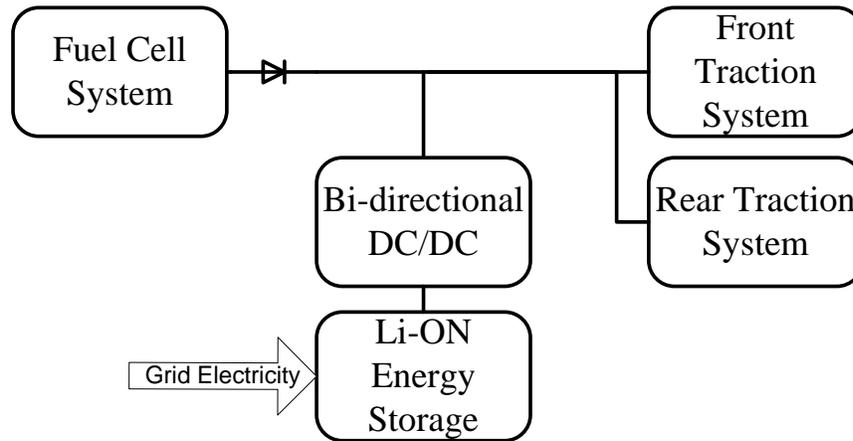
Figure 21: Fuel Cell Plug In Hybrid Electric Vehicle

Figure 22 shows the mechanical overview and physical locations of each powertrain component. The fuel cell system and majority of associated power electronics are contained under hood while the secondary energy storage system is contained at the rear of the vehicle. The hygdrogen tanks are found under the rear seats of the vehicle and electric traction systems are inline with both axles of the vheicle. Note for the ESS a Li-ion battery pack was selected based on the available battery modules, specifically that A123 provided 'strings' or 'modules' of cells and an associated battery management system for these modules. From these modules a pack was designed and built to intergrate with the fuel cell system and DCDC. Details of the battery pack will be discussed below.
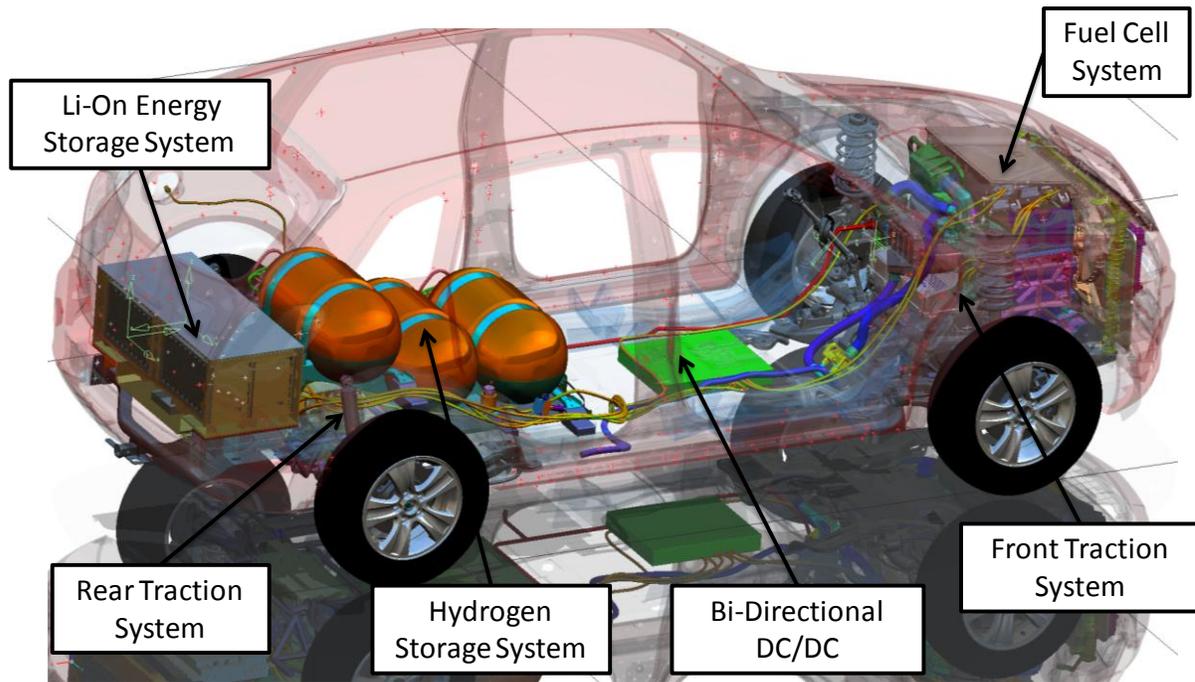
Figure 22: Vehicle Component Location Overview

The final specifications and VTS are given in Table 13 in comparison to the original base production VUE provided to schools and the competition minimum requirements. As actual testing of the vehicle as a whole has not yet been performed the results are from the latest vehicle modeling simulations.

Table 13: UWAFT Vehicle Specifications

SPECIFICATION	REQUIREMENT		
EcoCAR	**Production Vehicle**	**Competition**	**Team VTS**
Accel 0-60 (s)	10.6 s	≤ 14 s	9.4 s
Accel 50-70 (s)	7.2 s	≤ 10 s	4.3 s
Towing Capacity (kg, [lb])	680 kg (1,500 lb)	≥680 kg @ 3.5% 20 min @ 72 kph (45 mph)	680 kg (1,500 lb)
Cargo Capacity (m3, [ft3])	0.83 m^3	457 mm x 686 mm x762 mm	0.253 m^3
Passenger Capacity	5	≥ 4	2
Braking 60 – 0 (m, [ft])	38 m – 43 m (123 – 140 ft)	< 51.8 m (170 ft)	45 m (147.6 ft)
Mass (kg, [lb])	1,758 kg (3,875 lb)	≤ 2,268 kg (5,000 lb)	2,318 kg (5,111 lb)
Starting Time (s)	≤ 2 s	≤ 15 s	≤ 15 s
Ground Clearance (mm, [in])	198 mm (7.8 in)	≥ 178 mm (7 in)	165.1 mm (6.5 in)
Range (km, [mi])	> 580 km (360 mi)	≥ 320 km (200 mi)	354.4 km (220.2 mi)
Fuel Consumption, CAFE Unadjusted, Combined, Team: U.F. Weighted l/100 km	8.3 l/100 km (28.3 mpgge)	7.4 l/100 km (32 mpgge)	3.2 l/100km (73.5 mpgge)
Charge Depleting Fuel Consumption (l/km)	N/A	N/A	N/A (0 L/100km)
Charge Sustaining Fuel Consumption (l/km)	N/A	N/A	4.93 //100km (47.7 mpgge)
Charge Depleting Range (l/km)	N/A	N/A	50 km (31 mi)
Petroleum Use (kWh/km)	0.85 kWh/km	0.77 kWh/km	0.0029 kWh/km
Emissions	Tier II Bin 5	Tier II Bin 5	N/A
WTW GHG Emissions (g/km)	250 g/km	224 g/km	80 g/km

3.2 Combined Fuel Cell System and Front Traction System

The 93 kilowatt power plant fuel cell system was used in this work and came coupled to the GM ETS motor. The Fuel Cell System (FCS) has internal controls for air delivery, hydrogen injection, internal temperature regulation, water and humidity management, power electronics for the air compressor drive, high voltage coolant and fuel pumps. Since the FCS is coupled to the ETS their thermal management and mechanical integration becomes coupled as well. The integration of the fuel cell system is similar to that of an internal combustion engine (ICE) in that the fuel cell engine should be isolated from vibrations that arise in typical automotive environments. The mounting was designed to withstand 20g's of impact loading from that mass of its own body in all directions and meet reasonable installation and replacement times similar to that of a stock ICE.

Additional requirements required for the integration of the FCS system are as follows:

- External cooling of the fuel cell coolant by means of a radiator and pump;
- The thermal system must not contaminate the coolant and therefore special manufacturing of the radiators and heat exchangers is required to meet strict contamination guidelines;
- Supervisory control of the FCS is required to generate power to the vehicle sinks (i.e. traction systems);
- Filtered air free of contaminants is required for continued operation of the FCS in a vehicle; and,
- Continuous H_2 supply is required to produce electricity.

Table 14: Fuel Cell System Specifications

Device	Make/Model	Specifications	
Fuel Cell System	General Motors VER 4.5	Max Power:	93 kW
		Voltage Range:	260-371V
		Current Range:	0-375A

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Table 15: Front Traction System Specifications

Device	Make/Model	Specifications	
Front Motor	General Motors ETS	Peak Power:	110 kW
		Continuous Power:	80 kW
		Max Torque:	350 NM
		Gear Reduction (Fixed):	9.76
		Output Current:	390 A RMS
		Input Voltage:	180-450V
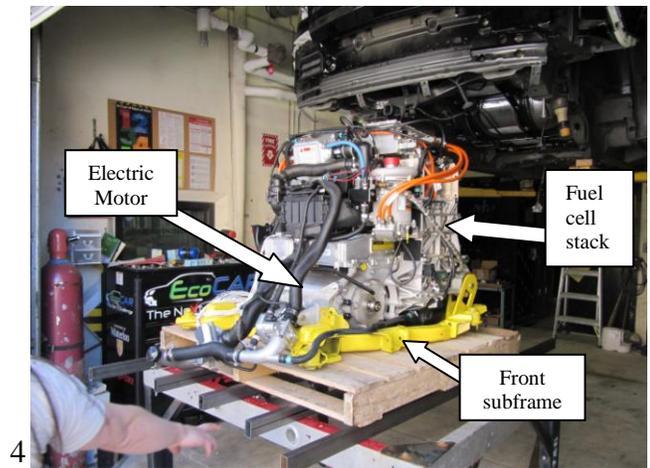
Figure 23: Fuel cell system coupled to front traction system and front subframe

3.3 Lithium-Ion Energy Storage System

Battery modules are provided by A123 Systems for use in the EcoCAR vehicle. For successful integration mechanical mounting and cooling of the modules into a pack was required. They may be cooled from the two sides of largest surface area or from the bottom of the module via liquid or air cooled plates.

After careful thermal design the team settled on a design that would evenly distribute the temperature among all cells and provide sound mechanical design for the energy source

shown in Figure 24 and Figure 25. Figure 26 shows the battery thermal design strategy for all four modules.

To aid in vehicle controls development the A123 system comes shipped with a battery management system that reports and controls the follows:

- Reports maximum allowable charge and discharge current;

- Report thermal information;

- Allows external safety interface for pre-charging the HV bus and closing safety contactors;

- Supervises all cells in battery modules and regulates their voltage with set limits; and,

- Monitors HV ground loops for safety.

Table 16: Energy Storage System Specifications

Device	Make/Model	Specifications	
Battery Pack	4 x A123 25S2P Prismatic cells	Voltage Range (Open Circuit):	315-340V
		Capacity:	40 Ah
		Energy:	12.9 kWh
		Power:	130 kW Peak, 40kW cont.

Figure 24: Battery Modules with Cold Plates on all Side Thermal Surfaces

Figure 25: Modules installed in final Enclosure
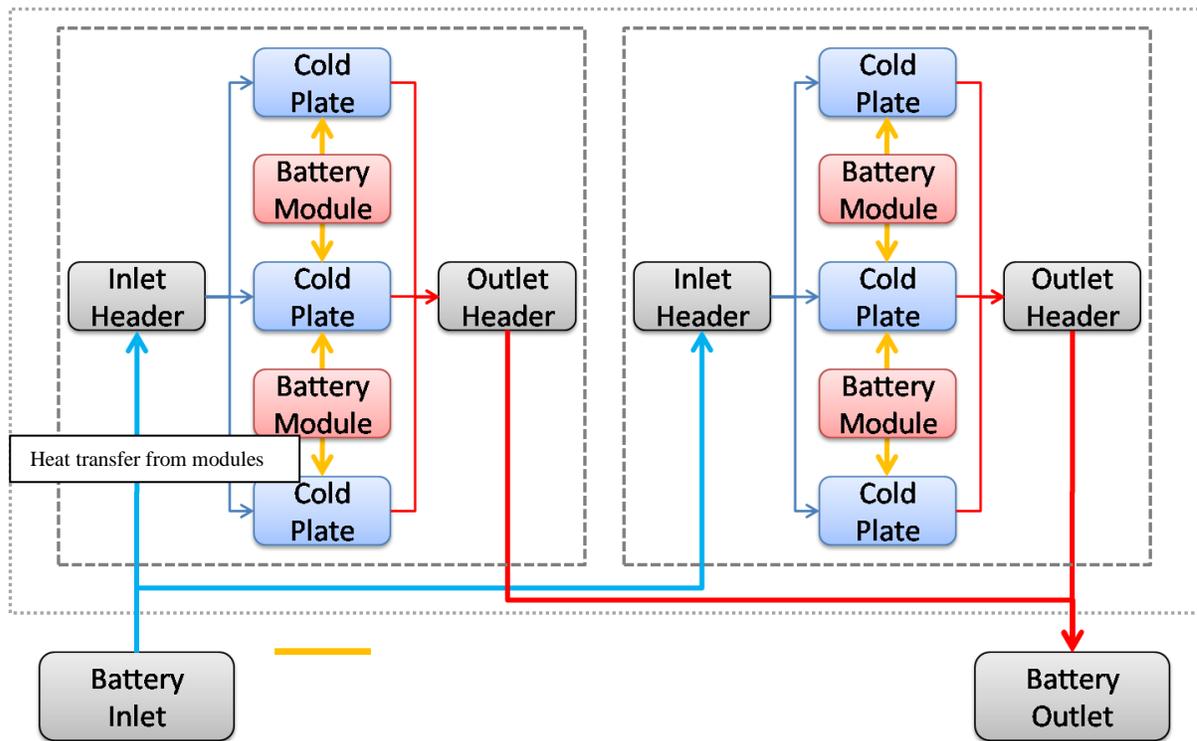
Figure 26: Battery Cooling Schematic

3.3.1 Rear Traction System

The Rear traction system works in conjunction with the front ETS traction system to propel the vehicle. Having a second traction system allows the vehicle to split torque front to rear to

improve drivability, performance, and potentially efficiency. The traction system specifications are provided in Table 17. A significant amount of mechanical design and integration was required for the implementation of the RTS. Figure 27 shows the interferences that would have been introduced if the stock rear sub-frame was used. Figure 28 shows the newly designed subframe that allowed for the successful integration of the system.

Table 17: Rear Traction System Specifications

Device	Make/Model	Specifications	
Rear Motor	Ballard 312V67/ Rinehart Inverter PM100	Peak Power:	67 kW
		Continuous Power:	32 kW
		Max Torque:	200 NM
		Gear Reduction (Fixed):	11.58
		Output Current:	300 A RMS
		Input Voltage:	120-450V
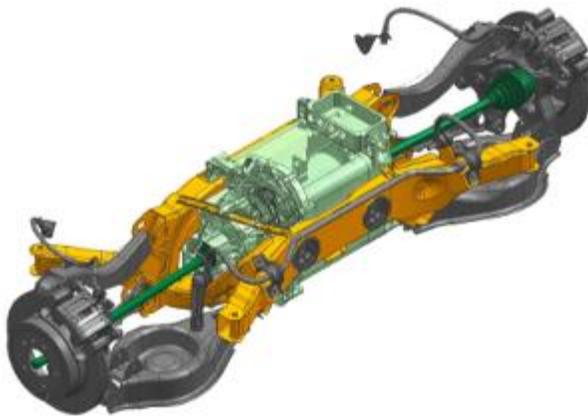
Figure 27: Interferences from the Ballard drive unit and the stock vehicle sub-frame.
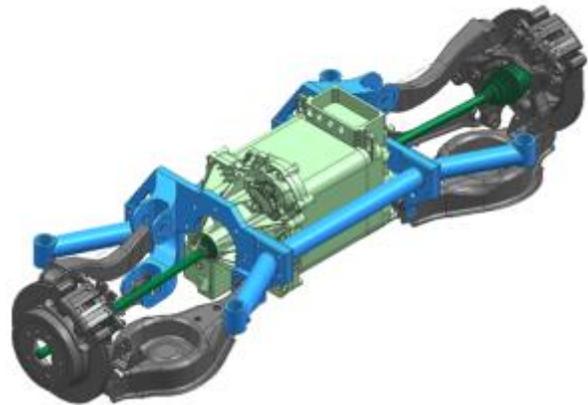
Figure 28: Newly designed rear sub-frame.

3.4 Bi-Directional DCDC

In order for the selected power sources to provide electrical power to the vehicle traction system and other HV loads a high power DC to DC converter is required to transfer current between the between the battery and fuel cell power rails. Both the FCS and ESS have transient variable voltages that vary with current, temperature, and battery state of charge. To achieve full performance and efficiency the DC/DC converter must transfer current in both directions (to and from the battery) with the ability to buck (step down) or boost (step up) the voltage in both directions. The converter is sized to meet the peak battery currents available so there are no limitations to the ESS performance. Without the DC/DC the overall system will become unstable with no ability to buffer the FCS during fast transient conditions. Durability and performance are key criteria to this component. Figure 29 illustrates the voltage variations of the FCS and ESS systems and the point at which the DCDC converter must switch from boost mode to buck mode. This is expected to be a daunting challenge for power delivery in the vehicle. Robust controls and testing will be necessary to ensure the safe transition between converter modes.
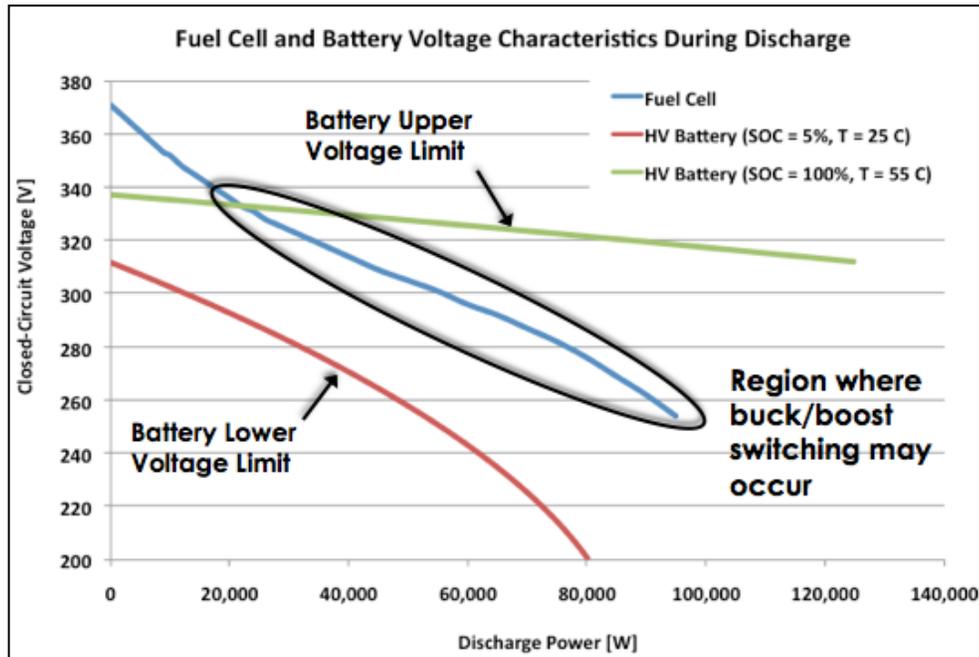
Figure 29: Difference in operating voltage of the GM fuel cell and A123 battery pack under various conditions and fuel cell power levels, showing the region where buck/boost is needed beyond approximately 25kW.

In addition to the layout and components above the following is required for successful implementation of the DC/DC:

- IGBT thermal management (cold plates with direct water contact to the modules);

- External control requests for current and operational modes;

- Internal closed loop current regulation;

- Internal supervisory safety controls; and,

- HV input and out within the designed voltage and current limits.

Table 18: UWAFT DCDC Specifications

Device	Make/Model	Specifications	
DC/DC Converter	Custom UWAFT Design and Construction	Input Voltage Range:	315-340V
		Output Voltage Range:	180-450V
		Converter Type:	Bi-directional buck-boost
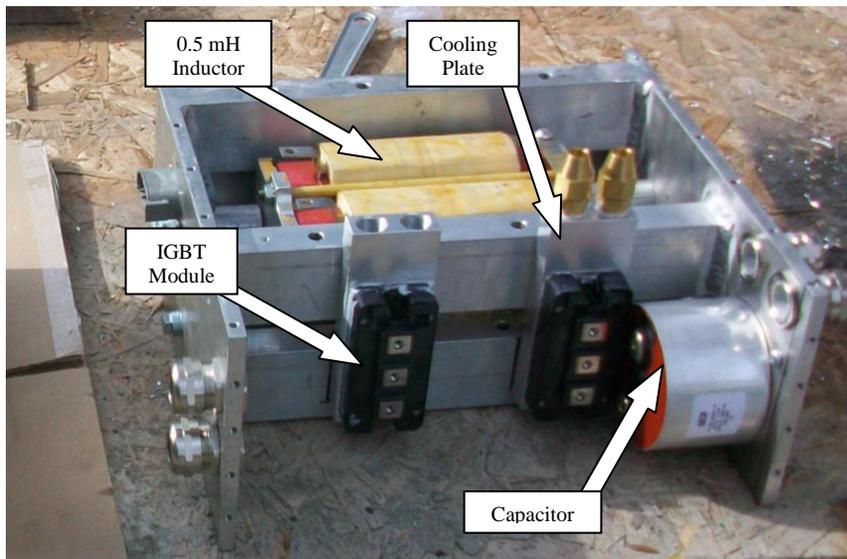
Figure 30: Partially assembled DCDC converter module

3.5 Hydrogen Storage System

The fuel cell system requires hydrogen in order to fulfill its purpose of supplying electricity to the vehicle power sinks. The HSS stores hydrogen at 700bar and regulates it to the required inlet pressure for the FCS of about 5 to 7 atmospheres. Contained within the HSS are on tank controllable valves, pressure relief valves, heating and cooling elements. In addition the entire system is monitored by multiple hydrogen sensors that will close the tank valves when threshold levels of hydrogen are detected. One should realize the large size of the tanks and the complex systems required for practical application. Finally because the

team decided to integrate a rear traction system the HSS had to be raised and pushed forward causing intrusions to the rear passenger compartment. To rectify this issue the tank structure was modified from its designed state and reconfigured to meet consumer acceptability standards in the vehicle.

Table 19: H2 Storage System Specifications

Device	Make/Model	Specifications	
Hydrogen Storage	General Motors	Max Pressure:	69 MPa (10000 psi)
		Tank Capacity:	4.2 kg
		Tank Volume:	181 L

Figure 31: GM/Quantum Hydrogen Storage System

Chapter 4

Hybrid Control Strategy Development and Baseline Strategy
Testing

The EcoCAR competition provides students with an opportunity to develop and test real world control systems for advance vehicle technology. A large number of control functions are required for the successful implementation of the powertrain and as with any significant software development it is driven heavily by software requirements.   In general, the supervisory controller is responsible for interpreting the driver's intentions and using the propulsion system to satisfy these intentions with uncompromised passenger safety, component protection and all within the specified functionality of the vehicle. Figure 32 shows the partitioning within the controller at a high level to convey the structure of responsibility, development and to help present a flow of understanding to those working on developing this controller. Each powertrain component in the vehicle has its own closed loop control system that will respond to requests from the supervisory controller and the current operating conditions. The three primary strategies or algorithms under development in the supervisory controller are the thermal, hybrid and torque control strategies. The thermal control manages all of the cooling, and heating systems in the vehicle to keep the powertrain components and the passengers within safe or desired operating conditions. For powertrain components this may include efforts to operate the component in a more efficient temperature region for overall vehicle efficiency gains. The hybrid control strategy (HCS) is primarily concerned with the power split algorithm to improve vehicle efficiency and is closely linked to the torque control strategy (TCS) that determines the amount of torque to request from each of the two electrical traction systems in the vehicle. The TCS includes torque splitting for efficiency gains, performance gains, functionality improvements and regenerative braking. While these algorithms are mainly concerned with efficiency gains that may be from novel approaches it is important to note that the most optimal solution may not always be possible especially in a vehicular situation where the driving conditions are

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unknown. To this end, there is a separation of the control strategies, like the TCS, from the actual component control which is shown in Figure 32. It is within the domain of low level component control that the TCS commands may be overridden based on safety protocols and vehicle modes. It is with this level of algorithm that has the final arbitrated command values to each component to ensure robust and safe operation of the vehicle. As one example, if the accelerator pedal were to fail during driving and was in turn commanding full torque from both motors, the actuation of torque disabling would be executed at this point.
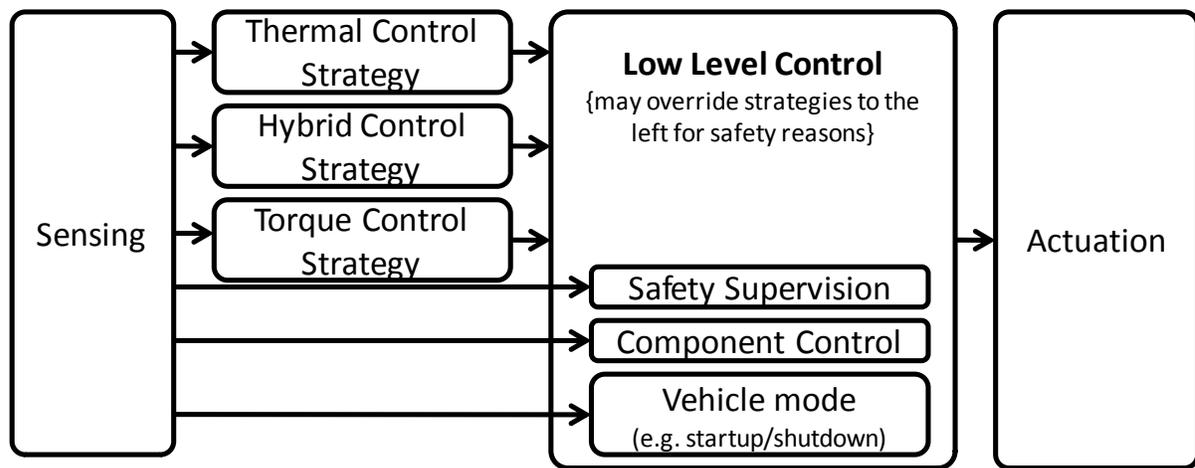
Figure 32: Supervisory Control Strategy Partitioning

It is expected that this architecture of the supervisory controller will have benefits to team work since it clearly separates certain control functions for development purposes. This partitioning of the strategy allows control objectives to be easily defined, documented and tested in parallel to the rest of the controls development. Further the intent is to allow each strategy to be implemented independent of the other strategy versions since the software timing may not always be inline. Not only does this architecture present benefits to workflow but it also provides useful segregation of software feature development for different skill levels and expertise. Typically in the past the majority of software controls were the responsibility of a few advanced senior or graduate students. This structure will promote the allowance for beginner students to be given responsibilities that are outside

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safety critical systems while more advanced team members can focus on higher risk diagnostics and actuation.

4.1 Control Requirements

The hybrid control strategy is required to output the fuel cell power request and DCDC current request at all times which will determine the power split between the vehicles two energy sources in order to satisfy the drivers demand and any other electrical loads in the system as a result of environmental or system conditions. It is favoured to complete these functions with the highest possible fuel efficiency while staying within the bounds of component specifications. While components like the fuel cell and battery have specified maximum propulsion power, and for the battery maximum regenerative power, it is important to note that because this system is real time and always changing these components report to the supervisory controller their maximum power limits on regular intervals via the controller area network communications bus (CAN bus). Therefore it is sufficient to say that the HCS and TCS must obey all instantaneous component limits reported to the supervisory controller. A summary of the strategies inputs and outputs are given in Table 20.

Table 20: Hybrid Control Strategy Inputs and Outputs

Inputs	Outputs
Battery Discharge Limit (Amps)	Fuel Cell Power System Request (watts)
Battery Charge Limit (Amps)	DCDC Current Request (Amps)
Battery State of Charge – SOC (%)	
Fuel Cell Maximum Power (Watts)	
System Power Demand (Watts)	
Charge Mode (Charge Sustain, Deplete or EV Only)	

4.2 Control Architecture

As stated earlier the supervisory controller being designed interacts with other closed loop systems in the vehicle. Figure 33 shows the relationship between this control system and the functions of the supervisory controller termed "torque decider" and "hybrid controller" which are synonymous with torque control strategy and hybrid control strategy. The torque decider generates a torque request that is sent to each electric traction system in the vehicle and the required power demand is calculated by the traction system and fed back to the supervisor.
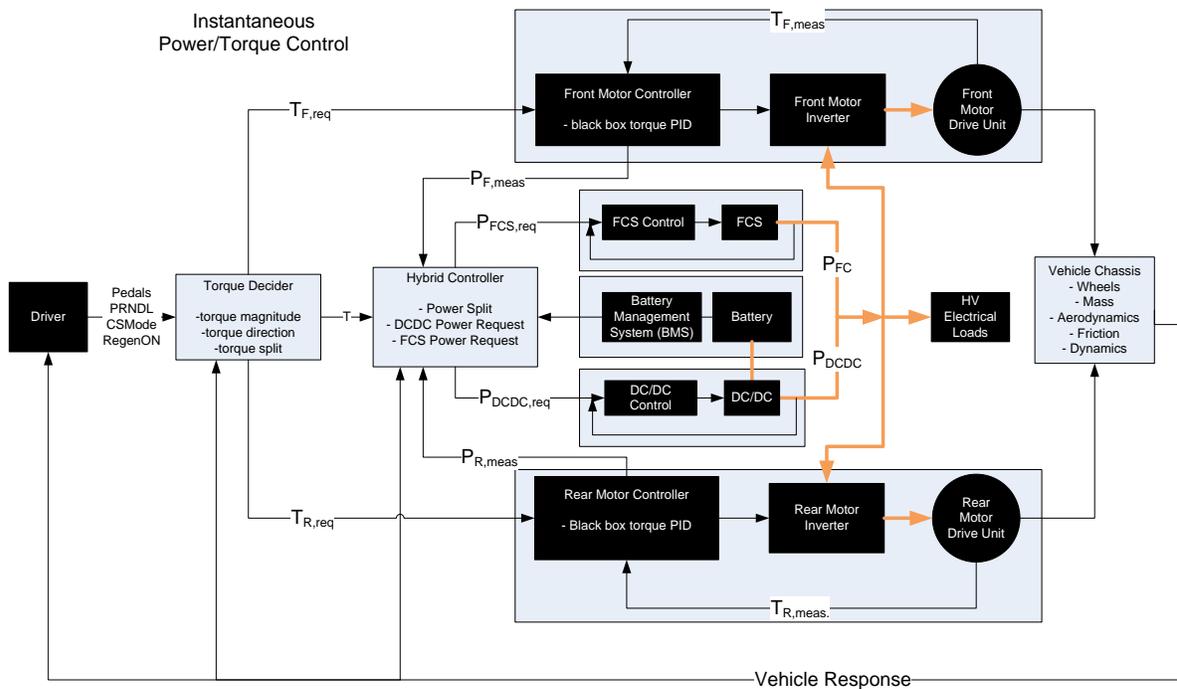
Figure 33: Instantaneous Power and Torque Control Diagram
 (Refer to APPENDIX B: Detailed Figures for larger diagram)

The TCS is plays an important role in the operation of the HCS since the torque requests make up the majority of required power in the propulsion system by an order of magnitude. Equation 8 and Equation 9 show how the torque request to the motors is formulated based on the minimum value of either the maximum available electrical power for propulsion or the

maximum physical motor torque limits and is then linearly scaled with accelerator pedal position. Realistic torque control will have more details and likely exponential pedal maps in relation to torque in order improve drivability of the vehicle. The efficiency of the traction systems will be based on manufacturers provided data as a function of speed and torque.

$$MaxTorque = T_{max} = \begin{cases} T_{max} = \dfrac{(MaxElectricalPower - Elec.Loads)\eta_{motor}}{MotorSpeed} \\ T_{max} = MotorTorqueLimit \end{cases}$$ **Equation 8**

$$Torque\,request = (AccelPedal\ \%\,)(T_{max})$$ **Equation 9**

The physical controls architecture consists of four CAN bus communication networks and a vast amount of low voltage wiring. The dSpace MicroAutoBox (MABX) serves as the primary supervisory controller that can interface with all components in the system and is the location of all of the control strategies discussed in this document to assist the MABX, a second controller from Mototron (112pin) is used for mid to high current applications like driving relays and cooling fans. Table 21 summarizes the controller names and functions that are presented in Figure 34. While this information is not directly important to the algorithm development it is important to understand the back ground of the sensing information and how it is provided to the supervisory controller. Each subsystem has low voltage automotive grade sensors which are often filtered at the subsystem level and then broadcasted over the communications bus for other controllers to read. It is also typical that the requests to each component subsystem are sent over the CAN bus. As a result of this architecture there is often time delay's and lag built into the system that can be attributed to the latency of CAN message transmission. This however is not discussed in the scope of this development as it extends much deeper into the hardware controls of the system and this section is concerned mostly with the algorithm development and implementation.

Table 21: System Controller Functions

Controller	Description
FCPS	General Motors Fuel Cell Propulsion System Level Controller (UWAFT uses only H2 functionality)
FCS	General Motors Fuel Cell System Level Controller
PMD	General Motors Power Management and Distribution Controls
ETS	General Motors Electric Traction System Controller
DS MABX	dSpace MicroAutoBox Supervisory Controller
MT 112p	MotoTron 112p ECU (for Current Driving and I/O applications)
RTS	Rear Traction System Controller (Rinehart PM100 inverter/controller)
A123 BCM	A123 Systems Battery Management System (CAN + LV interface)
HSS	Hydrogen Storage System
GM BCM	General Motors Body Control Module
H2 Sensors	Hydrogen Sensing System
DCDC	Bi-directional DCDC

Although not necessarily significant to the simulation, modeling and algorithm development of the vehicle's hybrid control strategy it is worth noting the physical layout of the control system in Figure 34.
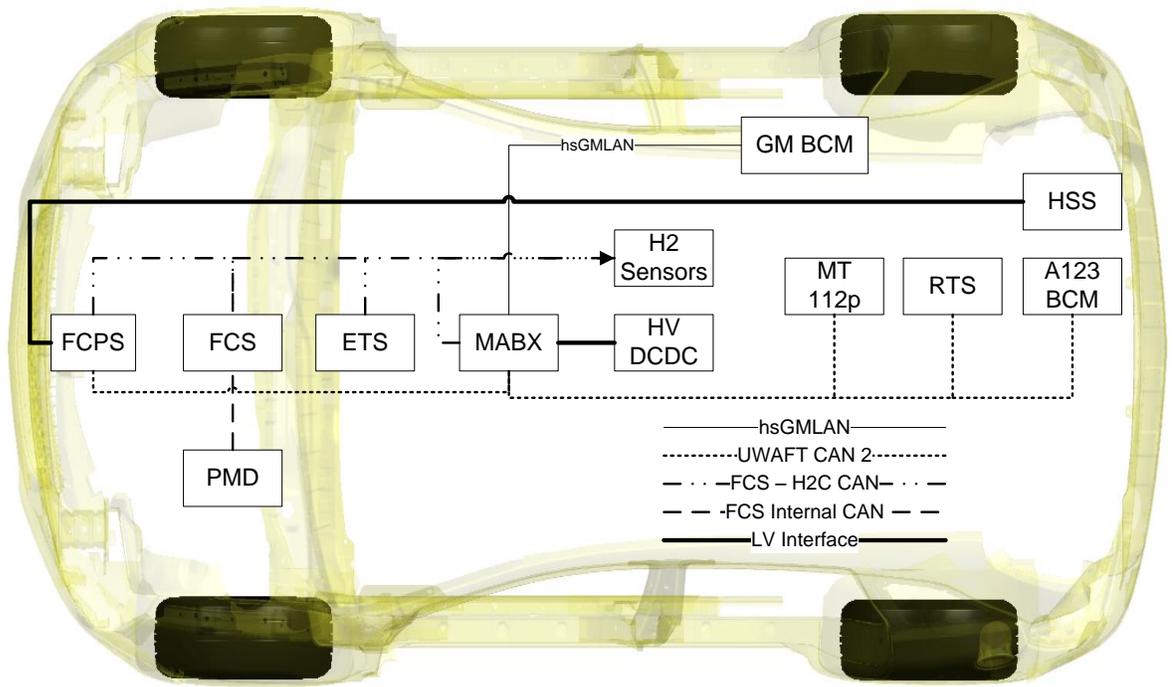
Figure 34: Hardware Controls Architecture

4.3 Algorithm Development

A three phase process is used to develop a pragmatic control strategy for use on board the UWAFT EcoCAR vehicle. Phase one simulated the base case control strategies identified in the literature and commonly referred to in industry as load levelling and load following strategies. In addition, a first stage engineering approximation is simulated in the same model. The model used for simulation is the plant model architecture described in Section 4.4. The model is an extremely useful tool used throughout the controls development for the vehicle and tends to include many relations that are based on manufacturer's data. During phase two a simplified vehicle model was created to perform an optimization routine developed in MATLAB. It is expected that the simplified model will lose some of the dynamic fidelity that is captured in the more involved Simulink plant model; however the main objective in developing this script is to observe patterns that can influence the strategy used onboard the vehicle. One important difference between the simplified plant model and the controls development model is that the drive cycles are completely known during the optimization routine allowing the power split to be optimized over the cycle whereas the controller in the phase 1 model is representative of the actual supervisory controller responding to driver inputs such as pedal position. Phase three uses the results and behaviour learned from phase one and two to modify the current vehicle's control strategy for improved and close to optimal efficiency. The phase three strategy will be evaluated and tested in the controls development vehicle model for determination on its feasibility for integration into the UWAFT vehicle. By design, the process will have inaccuracies associated with using to different plant models and the analysis of the results will attempt to identify these shortcomings and provide a path for improvement.
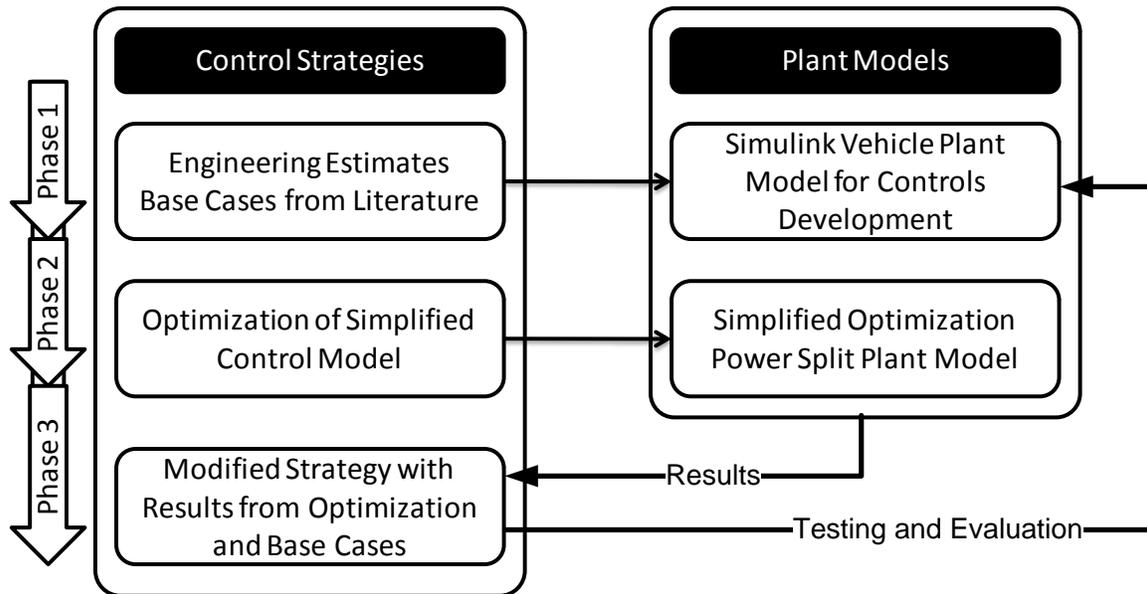
Figure 35: Strategy Development Plan

Phase one strategies discussed in the coming sections will summarize the rules used in determining the power split in each case. The important relation to consider is that the power demand in the system must be met by the combination of the fuel cell and battery energy. In addition for all control strategies used in the controls development plant model SOC demand is added to the overall power demand to ensure the SOC of the battery is sustained around 50% with upper and lower limits of 45% and 55%. When the low limit is reached the SOC demand will attempt to charge the battery with 10 Kilowatts (calibrateable) and scales back linearly as the upper limit is reached. The SOC demand is mainly implemented for situations unforeseeable in the control strategy design and will ensure SOC is always maintained over all driving conditions.

$$PowerDemand = FuelCellPower + BatteryPower$$
$$PowerDemand = SOC\,Demand + Traction\,Demand$$

Equation 10: Power Split and Demand

4.4 Vehicle Model and Component Models

In this document, to keep specific powertrain data confidential to the respective manufacturers, component models are described only on their flow and structure with respect to the powertrain controller and overall vehicle model. The majority of the controls simulation activities have made use of the following models and architectures have been useful for the evaluation of algorithms under development and the hardware testing of the control system using a hardware-in-the-loop bench setup. There is room for improvement on the fidelity and accuracy of the models, especially for transient operation and modeling of the dynamics expected to arise from the electrical architecture. For the purposes of baseline control strategy development and optimization analysis the models used are mainly energy and efficiency based to improve the initial speed of simulation. It is expected that as more dynamics are added to the models the speed will slow but the accuracy of the results will improve.

4.4.1 Overall Vehicle Model Structure

To streamline the controls process the supervisory controller under development is clearly separated from the rest of the vehicle model for easy partitioning and testing.

Figure 36 illustrates how the model begins with the driver on the left whose actions are interpreted by the supervisory controller and then acted upon by commanding the powertrain plant. The component plant models are covered in detail in the following sections.
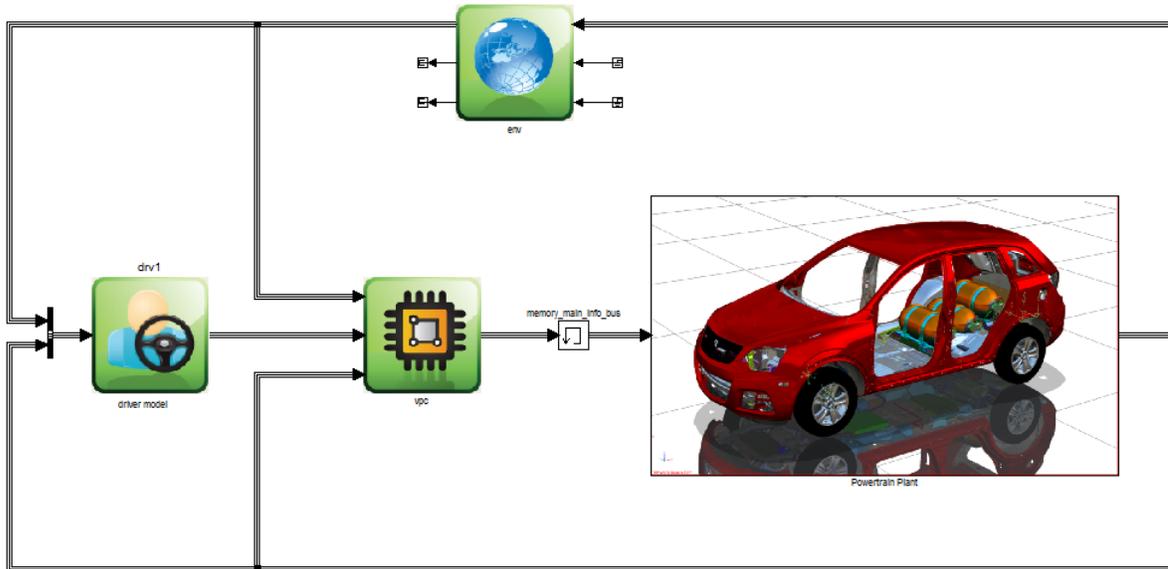
Figure 36: Vehicle Modeling Structure

4.4.2 Fuel Cell Model

The fuel cell system level model uses data provided by the manufacturer that represents the fuel cell stack plus the additional supporting components such as the air compressor and recirculation pumps. The information provided is the hydrogen consumption as a function of power and the system polarization curve as a function of output power. From this data one can extract the system voltage, current and fuel consumption depending on the output power from the FCS.

Table 22: Fuel Cell Model Summary

Inputs	Outputs	Required Data
Power Out [Watts] FC On [on/off]	FCS Current[Amps] FCS Voltage[Volts] FCS Hydrogen Consumption [grams/s]	Polarization curve (voltage vs. current) H_2 consumption vs. power curve

4.4.3 Battery Model

The battery model used is referred to as an electrical equivalent circuit that models the open circuit voltage of the combined cells and modules with an equivalent internal resistance as shown in Figure 37.[31] The data provided from the manufacturer is at a cell level and series and parallel calculations are performed to obtain pack level data. The internal resistance and open circuit voltage are given as a function of temperature and state of charge and used to calculate terminal voltage and output current as a function of power drawn from the battery with Equation 11 and Equation 12. The data provided also generates the maximum allowable power based on current limits provided as a function of SOC and temp.
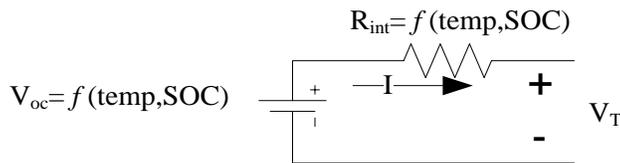
Figure 37: Equivalent Circuit Model [31]

$$V_T = V_{OC} - IR_{int}$$

Equation 11

$$I = \frac{V_{OC} - \sqrt{(V_{OC})^2 - 4R_{int}P_{batt}}}{2R_{eq}}$$

Equation 12

Table 23: Battery Model Summary

Inputs	Outputs	Required Data
Battery Power Output [Watts]	Output Current [amps] Terminal Voltage [volts] State of Charge (SOC %) Charge and Discharge Current limits [Amps]	R_{int} vs. SOC, Temp Voc vs. SOC, Temp Current limits vs. SOC, Temp,

4.4.4 Motor Model

For the two traction systems used in the vehicle, the team was provided with dynamometer test data that characterizes the system at a high level and gives the power losses as a function of motor torque, speed and voltage, which results in realistic efficiencies of the system.

Table 24: Motor Model Summary

Inputs	Outputs	Required Data
Rotor Torque req. [Nm] Motor Speed [rad/s] Input Voltage	Power Consumption[watts] Rotor Torque Achieved [Nm]	Torque vs. motor speed, power (power loss), voltage

4.4.5 Longitudinal Dynamics Model

The vehicle model used is derived from dynamometer test data provided by the manufacturer that uses the coefficients of F_0, F_1 and F_2 shown in Equation 13.

$$\sum \vec{F} = m\vec{a} = F_{app} - F_{drag} - F_{RR} + F_{grade} = m\frac{dv}{dt}$$

$where$

$$F_{drag} + F_{RR} + F_{grade} = RoadLoad$$ **Equation 13**

$or\, empirically\, (without\, grade)$

$$Roadload = F_0 + F_1v + F_2v^2$$

These coefficients correspond to the rolling resistance when velocity is of order one and aerodynamic drag when velocity is of order two and other losses that are not accounted for in the physical model are contained in the zero order velocity term. These coefficients effectively combine the values of the vehicle coefficients known as aerodynamic drag area, rolling resistance coefficient, and aerodynamic drag coefficient.

4.5 Initial Control Strategy Benchmarks

4.5.1 Initial Engineering Estimate

The initial engineering estimate is based primarily on the fuel cell system efficiency plot in Figure 38. From the plot one can see the poor efficiency region below approximately 10 kilowatts and trailing efficiency above 50 kilowatts. This creates a favoured zone of operation between the fuel cell lower efficiency limit and upper efficiency limit. The optimal fuel cell system efficiency is approximately 21 kilowatts.

Fuel Cell Efficiency Map - Points
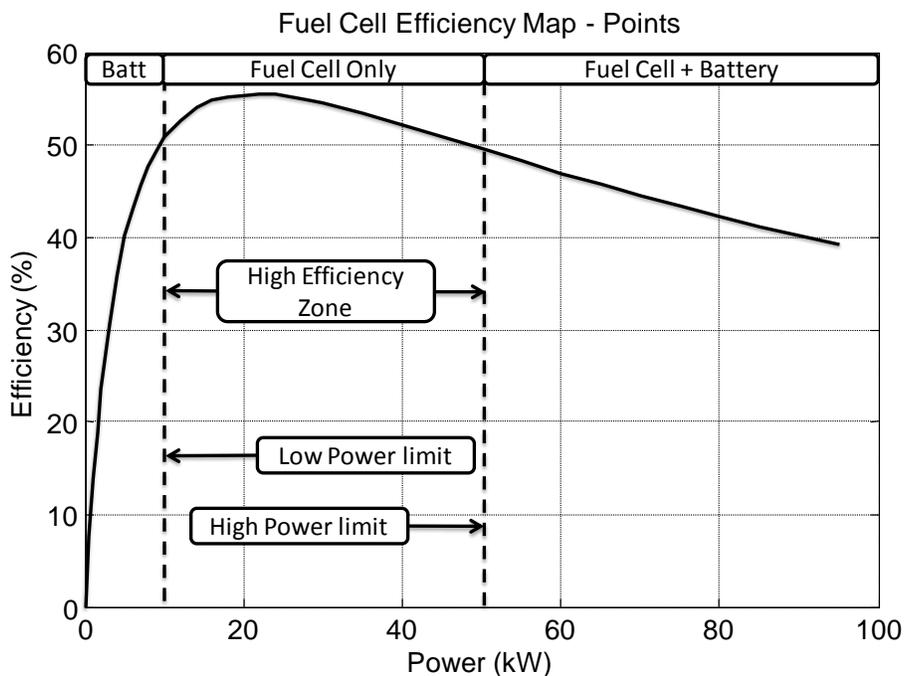
Figure 38: Fuel Cell System Efficiency Plot

The intent of this strategy is to favour fuel cell operation in its high efficiency region by pushing more of the load onto the battery when the power demand is outside of this region. Below 10 kilowatts the entire load is supplied by the battery and the load is shared between the battery and fuel cell when the power demand is above the fuel cell high efficiency limit. Table 25 summarizes the rules used in the engineering estimate and the results of the strategy

simulated in the controls development model are presented in Figure 39, Figure 40, and Figure 41. Note, at this time the fuel cell control system does not account for stop-start cycling of the fuel cell and the impact that this may have on the durability of the system.

Table 25: Initial Engineering Estimate Strategy Rules

Power Demand (traction)	FCS power request
Low Power (0 – FCS low efficiency limit)	0
Medium Power (FCS low efficiency limit – FCS High Efficiency Limit)	Total Demand
High Power (FCS high efficiency limit – (FCS high efficiency limit + Battery Max Power))	FCS High Limit
Peak Power (> FCS high efficiency limit + Battery Max Power)	Min[(Total Demand – Max battery Power) , Max FCS Power]
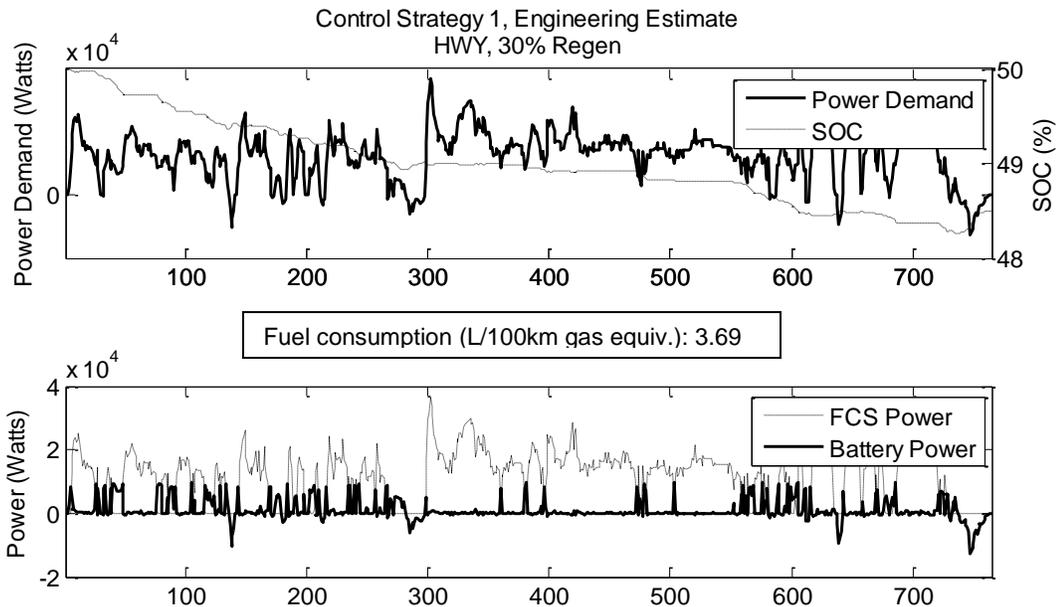
Figure 39: Initial Engineering Estimate Highway Cycle (30% Regen)
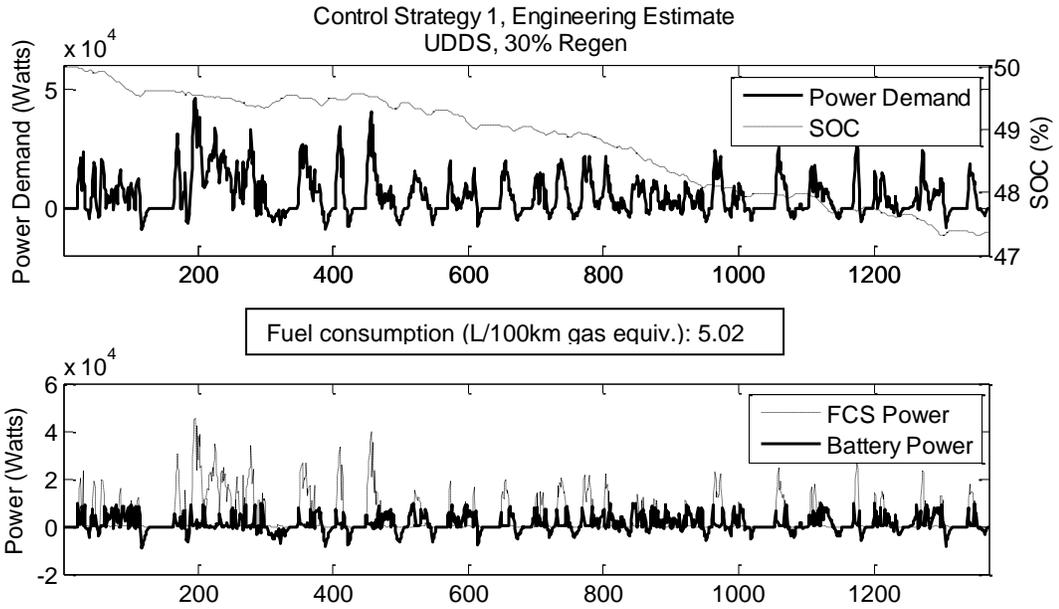
Figure 40: Initial Engineering Estimate UDDS Cycle (30% Regen)
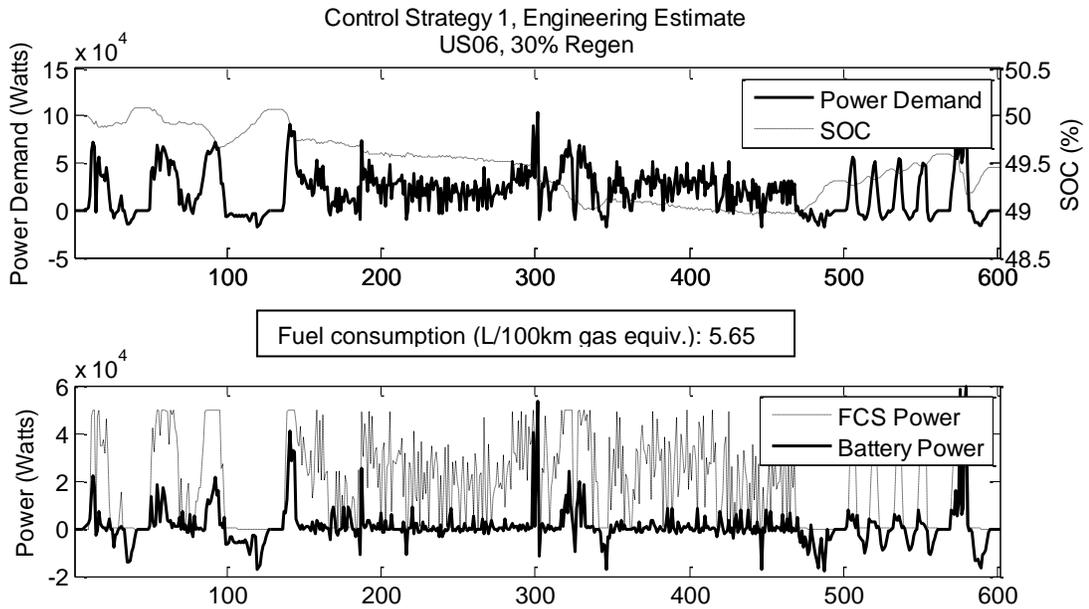
Figure 41: Initial Engineering Estimate US06 Cycle (30% Regen)

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4.5.2 Load Following Strategy from the Literature

The load following strategy uses the fuel cell as the dominant power source in the system providing the majority of the power demand to the traction system. The battery in this strategy will provide power below the fuel cell low efficiency limit and help with the higher power demands that the fuel cell cannot meet, especially during fast transients in the system. The rules for the load following strategy are listed in Table 26 and the results in Figure 42, Figure 43 and Figure 44.

Table 26: Load Following Rules

Demand	FCS Power
Low Power 0 - FCS Low Efficiency limit	FCS Power = 0
High Power >FCS Low Efficiency limit	Min (FCS Max Power, total demand)
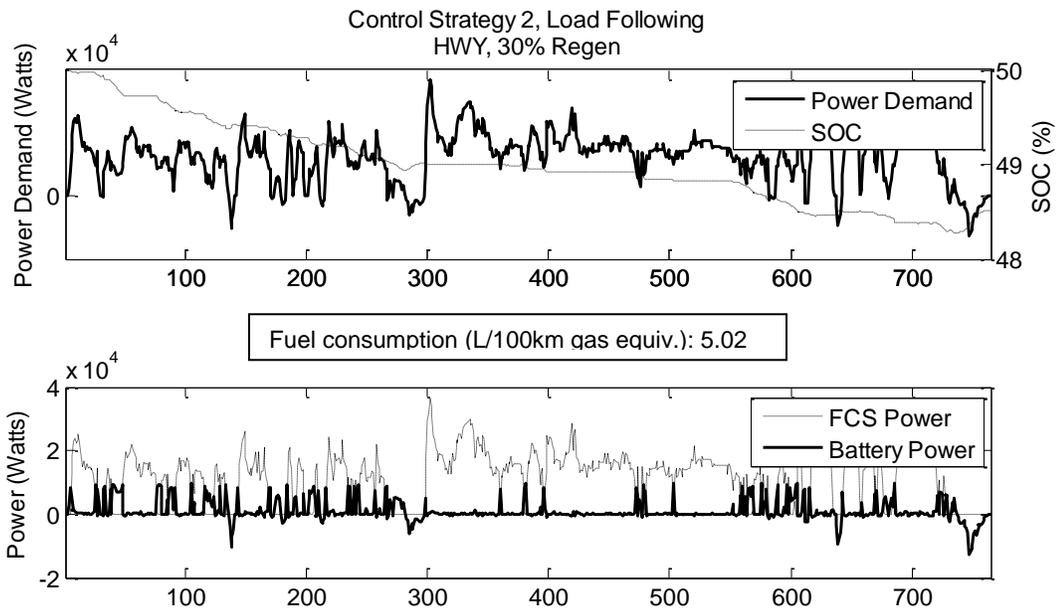
Figure 42: Load Following Highway Cycle (30% Regen)
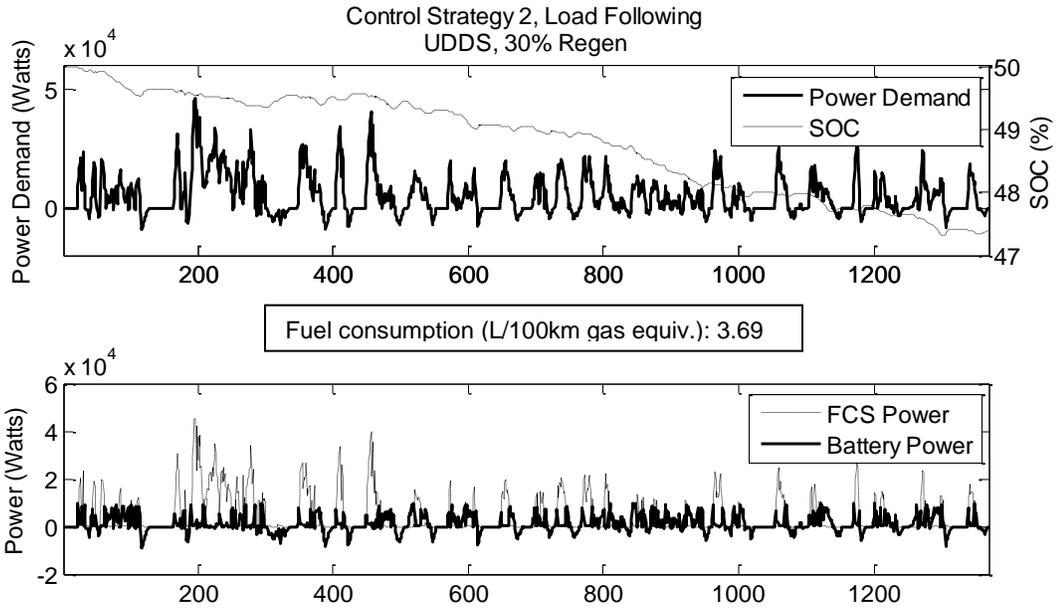
Figure 43: Load Following UDDS Cycle (30% Regen)
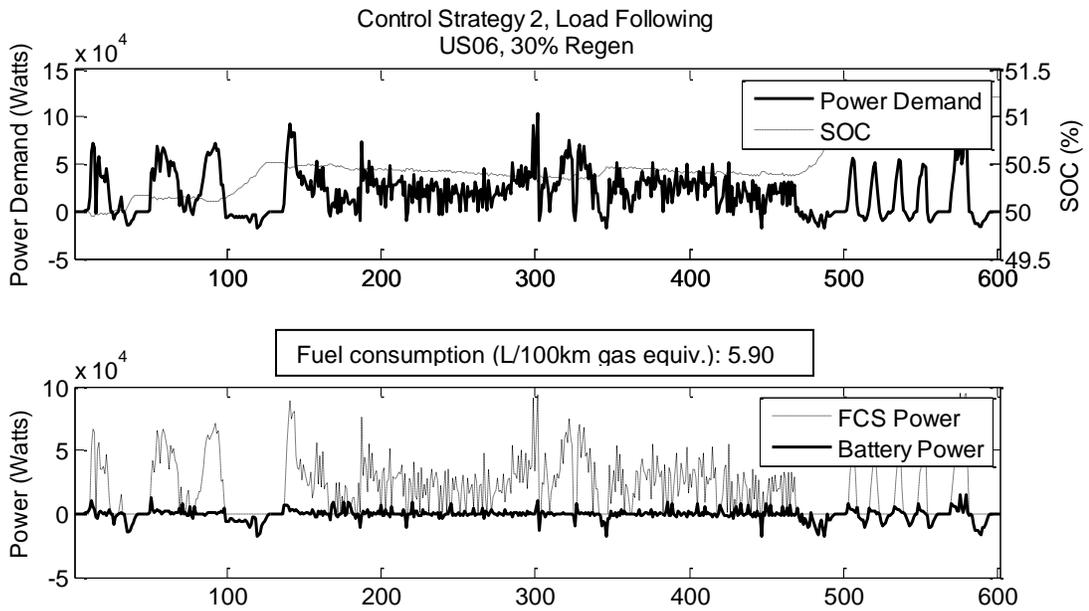
Figure 44: Load Following US06 Cycle (30% Regen)

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4.5.3 Load Levelling Strategy from the Literature

The load levelling control strategy puts much less transient load on the fuel cell but is still the main energy source for the vehicle. All of the transient power required in the system is supplied and absorbed by the battery, while the fuel cell is held at a constant and efficient power region. With this strategy usually the battery is required to have much more output power and at times when the fuel cell is off it may be required to meet the full power demand. Clearly this strategy has component architecture impacts and should be considered when evaluating using this method. For the purposes of this study the powertrain components are flexible enough to employ this strategy but for actual implementation into a vehicle the cost and benefits may need to be evaluated in more depth. For the load levelling strategy a wide open throttle condition (WOT) will turn on FCS if the SOC is high when normally it would be off, otherwise it will only turn on when the SOC has reached the low limit . In addition there is a minimum on time so it does not transition from on to off at a high frequency. The rules for the load levelling strategy are listed in Table 27 and the results from the controls development model are found in Figure 45, Figure 46 and Figure 47.

Table 27: Load Levelling Rules

Demand (traction)	SOC	FCS Power
<(FCS optimal + Max Battery Power)	SOC < SOC min	FCS optimal + SOC Demand
	SOC > SOC max	0
>(FCS optimal + Max Battery)	any	Min(Max FCS Power, Demand – Max Battery Power)
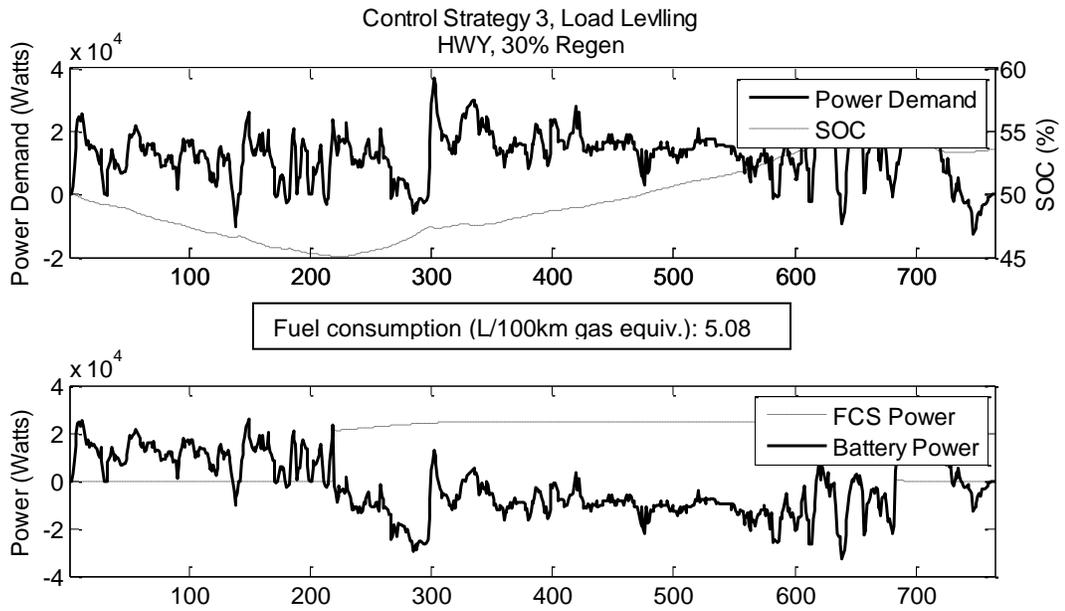
Figure 45: Load Levelling Highway Cycle (30% Regen)
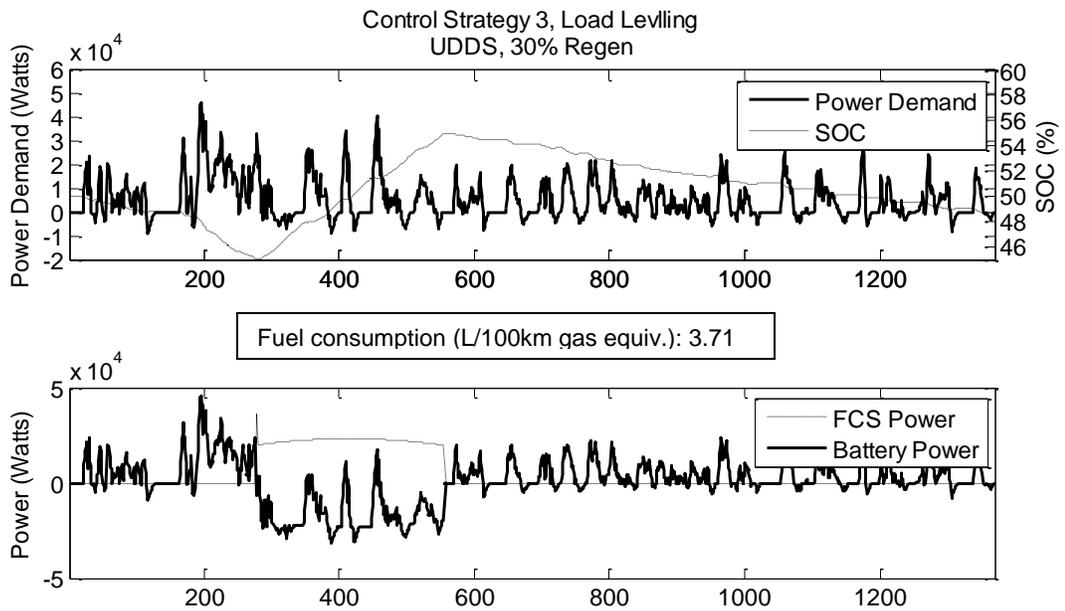
Figure 46: Load Levelling UDDS Cycle (30% Regen)

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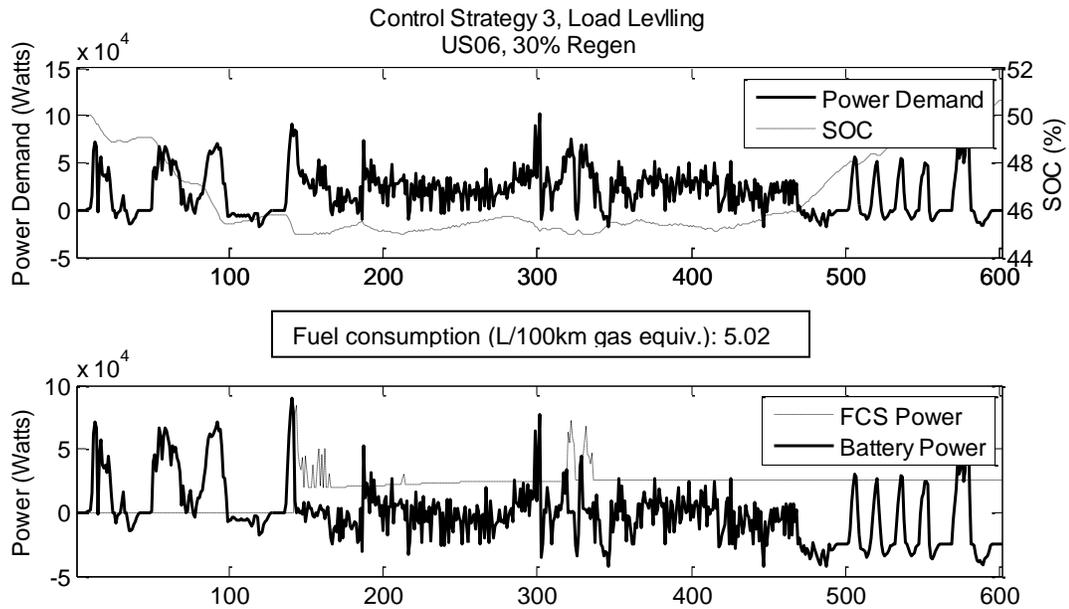
Figure 47: Load Levelling US06 (30% Regen)

4.5.4 Initial Simulation Findings

In general, the initial simulations focus on either stabilizing the fuel cell output or allowing it to follow the load, albeit with slightly different rules and operating regions. The initial engineering estimate focuses on trying to keep the fuel cell in its optimal efficiency region but only realizes system efficiency gains on the more demanding US06 drive cycle compared with the load following strategy. Although control strategy 1 and 2 had mild improvements on the city and highway cycles the load levelling strategy (control strategy 3) realized significant gains over the first two control strategies during the US06 cycle. It is important to note that the average power demand of the US06 cycle is extremely close to the peak efficiency zone of the fuel cell which provides significant benefits to load levelling the fuel cell in terms of system efficiency. This means that there will be less charging and discharging of the battery which is more apparent in the less demanding drive cycles.

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Chapter 5

Optimization Results and Modified Hybrid Control Strategies

5.1 Optimization Analysis

In an effort to determine the absolute lowest fuel economy attainable over a given drive cycle constrained, non-linear programming methods were used over three different drive cycles: the city, highway and the more demanding US06 cycle. The constraints used in the algorithm can be found in Table 28. The constraints ensure that the battery charge sustains over the entire cycle, and maintains a 10% operating window centered around 50% SOC for the battery pack. The components are limited to their maximum power levels without any temperature degradation. Component models are based on those described previously with no dependence on SOC or temperature since the SOC is assumed to not change significantly over the cycle. The performance would however be a strong variation of SOC during charge depleting operation but is not within the scope of this optimization. The results from each drive cycle are presented graphically and with charge sustaining fuel economy results in Figure 48, Figure 49, and Figure 50. For realistic results only 30% of the available regenerative braking energy is captured and stored in the battery. For details on the programming details of this optimization please refer to Appendix A for the source code.

$$\arg\min \begin{cases} f(x) = \sum_0^t \dot{m}_{H2}(x,t)dt \\ s.t. \\ See\ constraints \end{cases}$$

Equation 14: Cost Function

Table 28: Optimization Constraints

Battery SOC	45 – 55 % for all time SOC(0) = 50% SOC(end) > SOC(0) (to charge sustain)
Battery Power	-50kW < Pbatt< 130kW
Fuel Cell Power	0 < Pfc < 93 kW
Power split	Battery Power + Fuel Cell Power = Power Demand (at each time step)

5.1.1 Simplified Optimization Plant Model

To combat the processing time involved with executing an optimization routing in MATLAB a number of simplifications were made to the vehicle model.

1. Constant battery resistance

Although not provided in this paper, due to confidentiality concerns, when the battery internal resistance plots are examined the charge and discharge values are approximately equal and constant over the range of interest (50 % SOC and 40 to 50 degrees Celsius).

2. Power demand and Inverter voltage input effects.

The power demand used in the power split optimization is calculated directly from the chassis model described in Section 0. This removes any of the latency from the driver model and motor models that is captured in the more involved controls development plant models. In addition only the efficiency tables from the GM ETS are used in determining the power demand, meaning the front and rear motor are assume to be the same efficiency.

3. Required torque achieved by meeting the power demand in 2.

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The power demand generated by the chassis model will be assumed to convert to the torque required for the vehicle to meet the drive cycle. The controls development plant model takes into account more transient effects and thermal related performance however the scope of the optimization is constrained by the power demand vector and will remain constant during the simulation.

5.1.2 Optimization Results
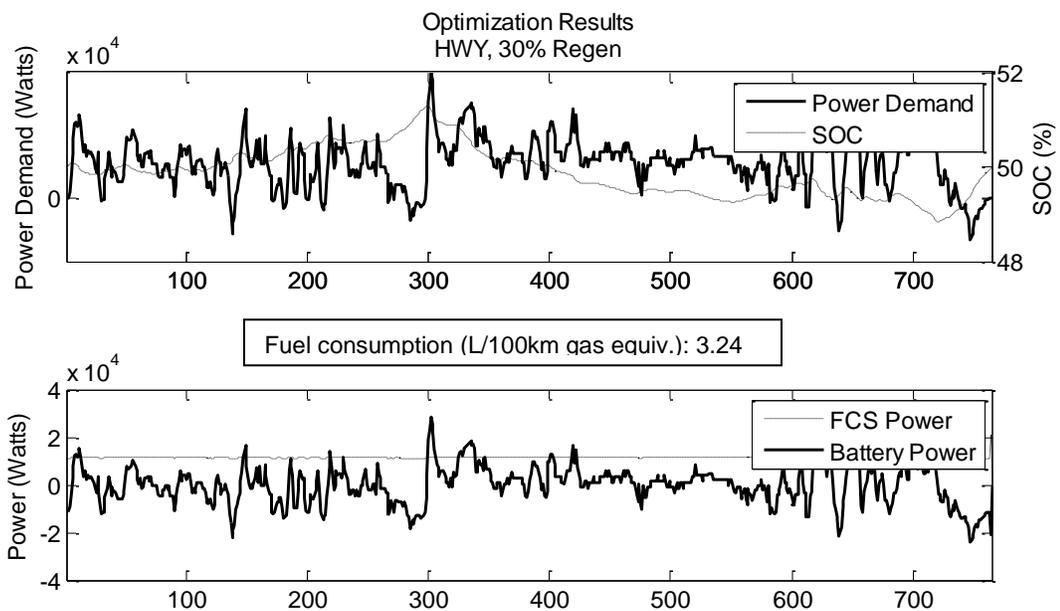
Figure 48: Optimization results using HWFET cycle with 30% of regenerative braking energy captured
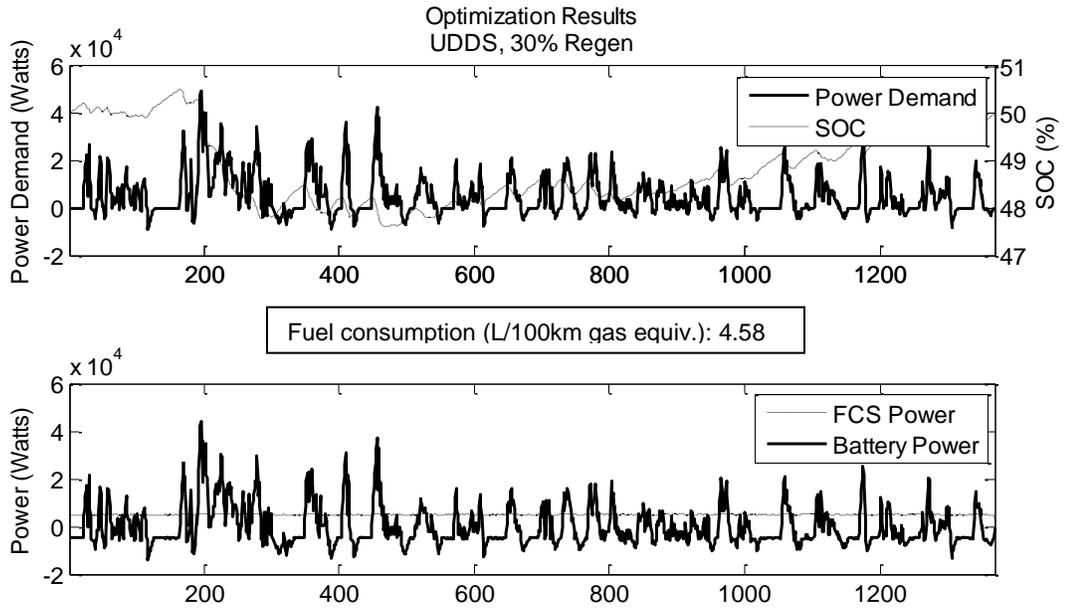
Figure 49: Optimization results using UDDS cycle with 30% of available regenerative braking energy captured
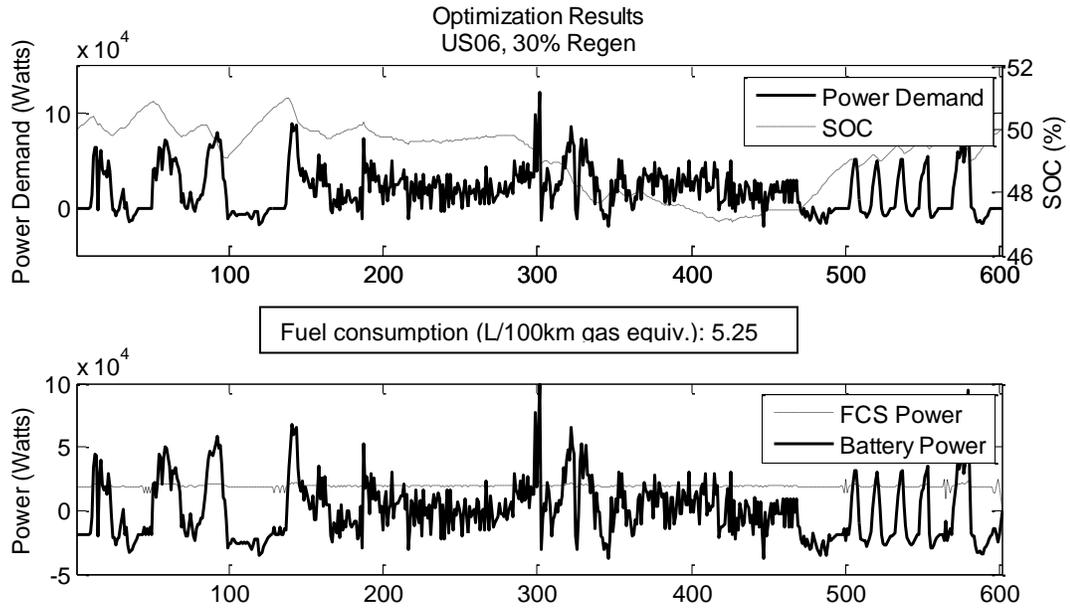
Figure 50: Optimization results using US06 cycle with 30% of available regenerative braking energy captured

Table 29: Summary of optimization results over the UDDS, HWFET and US06 drive cycles L/100km (Miles/Gal-Gas eq)

Cycle	30% Regenerative braking
UDDS	4.58 (51.29)
HWFET	3.24 (72.44)
US06	5.25 (44.76)

Table 30: Drive Cycle Characteristics (pre-electric traction system)

Cycle	Average Propulsion Power (30% Regen)	Electrical Energy Consumption per Kilometer at traction system input (wh/km)
UDDS	5.0 kW	157
HWFET	11.3 kW	145
US06	19.0 kW	246
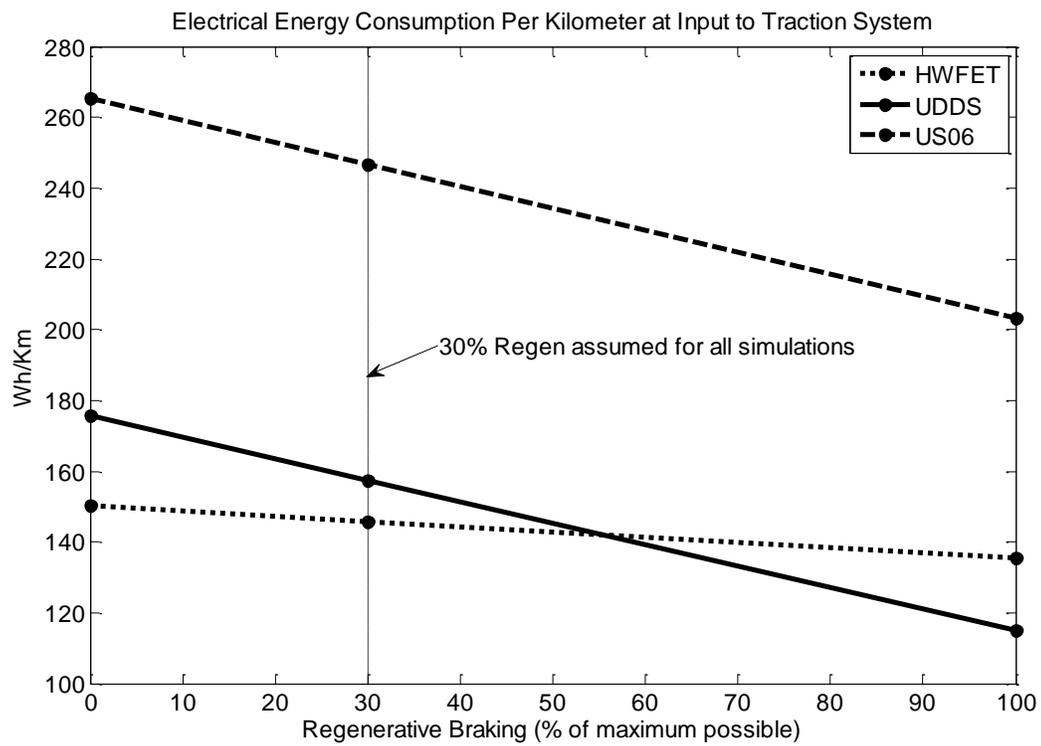
Figure 51: Electrical Energy Consumption per Kilometer at Traction System Input

5.1.3 Analysis of Optimization Results

There are two key observations from the optimization results but keep in mind that the patterns observed are more important than the actual raw fuel economy numbers when comparing to the base cases. This is primarily due to the plant model differences and simplifications to aid in computation time.

1. Load levelling fuel cell operation

It is immediately apparent when inspecting the graphs for each drive cycle that the favoured operation of the system is to load level the fuel cell at a constant power level.

2. Fuel cell operating point and drive cycle dependencies

Even more interesting is that the power level varies proportionally to the aggressiveness of each particular drive cycle. In this case aggressiveness is referring to the average power characteristic of the drive cycle. Intuitively this makes sense as more aggressive cycles have higher power demands and will ultimately require higher power from the propulsion system. The power level for the fuel cell found to be most optimal correlates very closely with the average propulsive power of each drive cycle which is summarized in Table 30. To further help compare drive cycles the energy per kilometer is provided at the traction system input. This metric shows that the most aggressive cycle, or the cycle with the highest average power, may not necessarily have the lowest fuel consumption, as is the case when comparing the UDDS to the HWFET. For example, in Figure 51 the energy per kilometer required at the traction system input depends on the amount of regenerative breaking energy captured. Since the UDDS has a significant amount of acceleration and braking compared to the HWFET, if the vehicle's kinetic potential energy is not captured through regenerative braking then the energy per kilometer metric will suffer. For the UDDS cycle the change in energy consumption varies from 114 wh/km to 175 wh/km when the regenerative braking percent is varied from 100% to 0% while the highway cycle varies from 135 wh/km to 150 wh/km in the same situation illustrating the highway cycles is not significantly affected by changes in

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regenerative braking. In any case, all simulations in this study are performed at the same level of 30% regenerative braking allowing for consistent comparison across control strategy modifications.

It is often found in the literature that even for engine based series hybrids that the supervisory controller will attempt to place the engine at its peak operating efficiency, however based on these results it is not merely the fuel cell system efficiency that is important but rather the powertrain system efficiency and corresponding vehicle fuel economy. By load levelling the fuel cell at its peak efficiency, approximately 21 kW, for most drive cycles this would result in extra charging and discharging cycles of the battery leading to more energy lost in the form of heat due to the batteries internal resistance. Selecting a lower fuel cell power that avoids unnecessary charge and discharge cycles of the battery leads to a higher overall system efficiency. This provides significant insight into the relationship between the aggressiveness, or average power demand of a particular driver or drive cycle and the set point for a primary power plant in a charge sustaining hybrid. Since it is difficult to gain an a priori knowledge of any given drive cycle, adaptive algorithms that are based on historical average driving data could estimate a driver's characteristics and modify, for instance, the preferred set point of an engine to target higher system efficiency. Vehicle controllers could contain multiple parameters to characterize multiple drivers of a vehicle while still having default set points for unknown or unexpected situations.

5.2 Control Strategy based on Initial Estimates and Optimization Results

After analyzing the results from the initial estimates, baseline cases and optimization simulations a new modified control strategy was developed. This strategy is based strongly on the base case load levelling strategy but with a modified operating point for the fuel cell system. Since the optimization results illustrate that if the fuel cell can be operated at or near the average propulsion power it will produce the optimally efficient power split. Therefore, an average power calculation is developed and simulated for illustration of this concept.

Figure 52 shows the flow of this new set point implementation. What may not be inherently obvious about this calculation is that it is easily implemented in a real-time control system.

Often complex optimization routines are too computationally intense to compile and flash to typical vehicle system microcontrollers. This always should be the objective of an optimized algorithm since without the element of practicality the results through simulation realistically cannot be achieved. In this particular case the control strategy is being written in a the vehicle controls development model which will transfer directly to the vehicle level controller upon completion.

 Figure 53, Figure 54, and Figure 55 show the results of the final strategy tested over three drive cycles.
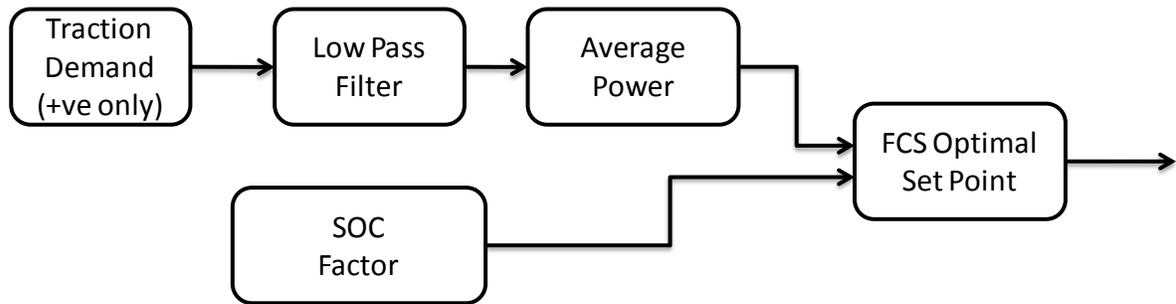
Figure 52: FCS Optimal Set Point Calculation
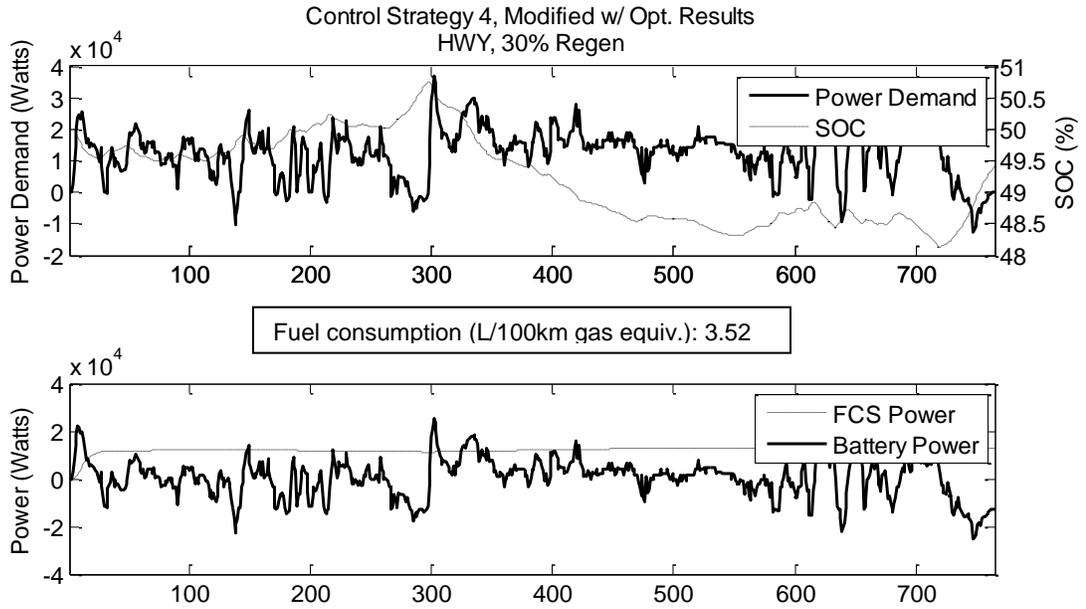
Figure 53: Modified Control Strategy Highway Cycle (30% Regen)
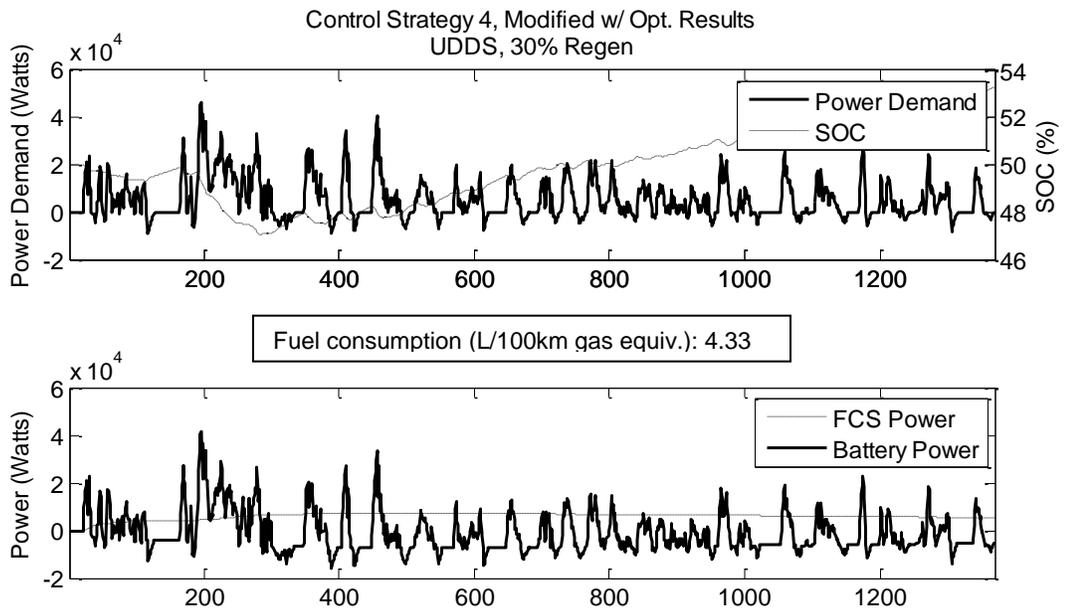
Figure 54: Modified Control Strategy UDDS Cycle (30% Regen)
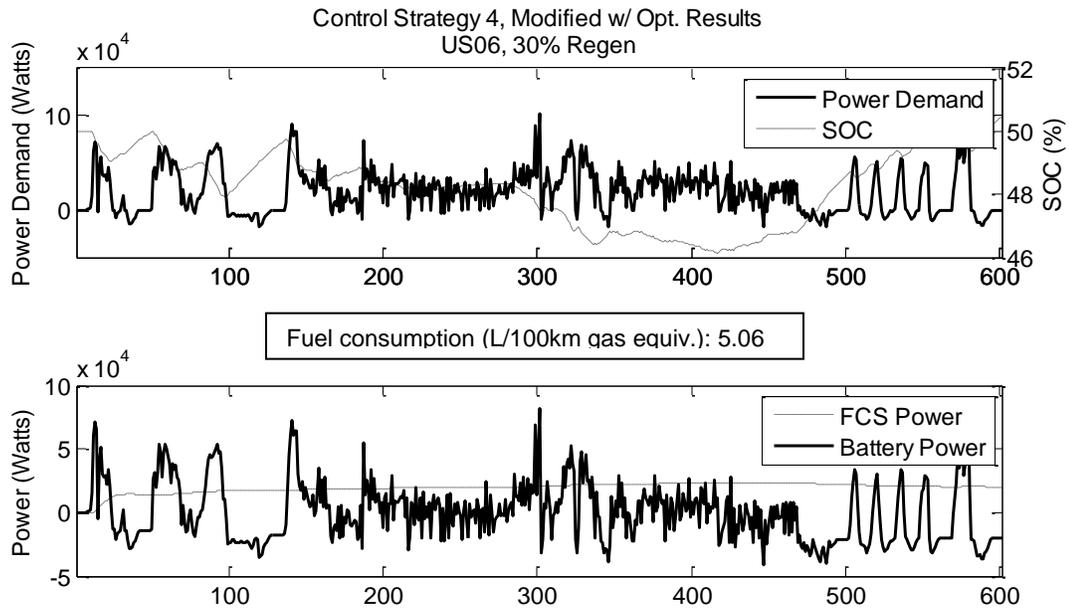
Figure 55: Modified Control Strategy US06 Cycle (30% Regen)

5.3 Results Summary

- City driving experienced the highest gains.

Although this paper is not primarily directed at comparing drive cycles it is interesting to note that the city cycles had between 13.8% and 14.9% improvement over control strategies 1 through 3. At the very least this shows there is research potential for correlating control strategies to the actual driver behaviour and further using drive cycles as inputs to a vehicle control system.

- Hwy driving had the smallest gains

The percentage gains of the modified control strategy over strategies 1 through 3 ranged from 4.7% to 5.3%. This can be explained by looking at the average power consumption in Table 30. During the initial estimates in the load levelling category the fuel cell set point was fixed at 21 kilowatts. The average powers for the highway and city cycle are 11 and 5 kilowatts

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respectively. As a result the difference between average cycle power and the actual output of the fuel cell is much higher in the city cycle which will lead to more charging and discharging of the battery and hence leave more room for improvement with the modified control strategy 4.

- Range from 3-15% gains by optimizing controls

The important observation is that all cycles realized system efficiency gains with the modified control strategy based on results and behaviour of the optimization exercise. As mentioned above it may be possible to further improve the results of an individual cycle and control strategy however that is leaving the scope of this research.

- For non-optimized controls the drive cycle may dictate the best starting strategy if there is no time to optimize.

The US06 cycle had significant gains when using load levelling compared to the other initial strategies. The city and highway cycles were not significantly impacted by the initial strategy choice. It should be noted that the average power of the US06 cycle is very close to the default initial fuel cell set point of 21 kilowatts which may contribute to this large efficiency gain in the base case testing.
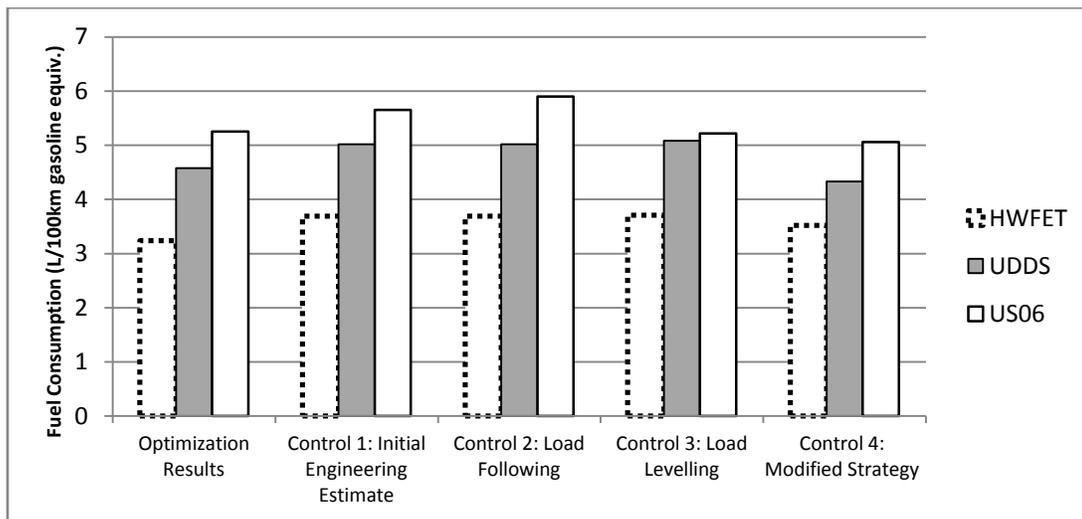
Figure 56: Fuel Consumption Results Summary of Highway, City and US06 Drive Cycles

Table 31: Summary of all simulation results (l/100km)

Drive Cycle	Optimization Results	Control 1: Initial Engineering Estimate	Control 2: Load Following	Control 3: Load Levelling	Control 4: Modified Strategy
HWFET	3.24	3.69	3.69	3.71	3.52
UDDS	4.58	5.02	5.02	5.08	4.33
US06	5.25	5.65	5.90	5.22	5.06

Drive Cycle	% Change of Control 4 with Control 1	% Change of Control 4 with Control 2	% Change of Control 4 with Control 3
HWFET	-4.7%	-4.7%	-5.3%
UDDS	-13.8%	-13.8%	-14.9%
US06	-10.5%	-14.3%	-3.0%

Chapter 6

Conclusions and Recommended Future Work

6.1 Conclusions

1. Optimized power split solution is load levelling the fuel cell system operation operating close to the average propulsion power at the traction system input.

The first and primary conclusion from the controls strategy development and optimization exercise is that the most optimal power plant operation is load levelling. Further, the set point for the fuel cell is not the point that results in the most efficient power conversion of the component but rather the point that contributes to the highest system efficiency. As a result of the complicated interactions and dependencies this set point is not obvious at first and this exercise can lead to achieving close to the maximum system efficiency. By choosing the system efficiency as the parameter to focus on the extra charging and discharging of the energy storage system is minimized and contributes to significant overall system efficiency gains.

2. Specific drive cycle knowledge can be use to optimize system efficiency.

The optimization routine illustrates how one can optimize the system efficiency when the entire drive cycle is known. In an effort to make the controls strategy compatible with a real-time environment past driving data was used to compute a running average power that will influence the fuel cell set point during run time. This leads to the point that by attempting to achieve a priori knowledge of the drive cycle the control system may benefit and can run more advanced optimization in real-time. Past, present and future drive data can be combined to achieve this information. This research work illustrated how just one of these categories can contribute to improving the system efficiency.

3. Real-time compatibility must be considered when development control systems destined for in-vehicle operation

In vehicle systems, the ability to optimize offline with prior knowledge of the driver inputs does not provide any tangible connection to real-time control systems. The focus should be always to develop software that can either be implemented directly in real time embedded systems or with minimal modification.

4. Simplified models speed up the optimization exercise and still allow for strategy comparison and trends analysis

Ideally the controls model used for development would be the same model used for optimization of the system. The nature of the models and optimization routines caused some incompatibilities that required simplified models to be developed for the optimization exercise. Although some accuracy was lost it was illustrated that this method can provide a quick way to recognize patterns in the controls system that can feed into the actual controls development model to realize system efficiency gains.

5. SAE J1711 fuel economy calculations are not sufficient for helping consumers understand the operating costs of new vehicle

Although recognized mostly through this research and not directly computed in the results, the methods used in SAE J1711 are useful for fleets and average national calculations but do not give the consumer a reasonable estimate of their expected fuel consumption. When EPA fuel economies for conventional vehicles were very close to the actual real worlds results it was a reasonable estimation for consumers to calculate their total annual costs. Now there needs to be a method to help consumers understand the realistic costs for vehicles with more advanced power trains and more diverse modes of operation, and it is likely that this method would have to include some type of drive cycle evaluation to fit powertrains and/or control systems to driver behaviour.

6.2 Recommended Future Work

As with most research, the knowledge and insight gained through the development process brings to light items that the author would change if there was time. This leads to a few focused recommendations for future research and development in the areas of model based design and powertrain controls. The list below organizes some of the improvements that can be made to the presented research and other areas of potential research discovered through this project.

The first two recommendations are enhancements and additional tasks that can be associated with the research presented in this paper. The third serves as potential related research. Items four and five are related to the vehicle implementation of control strategies described in this paper and the core teachings required in producing competent engineers knowledgeable in the areas of powertrain controls development , modelling and simulation.

1. Accuracy of simulation models

As mentioned in areas of this research some simplifications were made to the models used in development to aid in execution time and model creation time. Emphasis on creating more dynamic models with higher fidelity can improve the simulation accuracy.

- Investigate dynamic models, including:
    - Optimization models with dynamic power demand as a function of bus voltage. For example the power output of the fuel cell will affect the bus voltage and therefore the traction system efficiency.
    - Connect the optimization models and controls development models so that a single vehicle model can be used for both processes without simplification.
    - Thermal dependencies and temperature effects on system efficiency

2. Run optimization for charge depleting and blended operation

Even though the vehicle architecture selected is capable of charge depleting the primary starting point for the power train controls is to successfully implement the charge sustaining modes. Since there is flexibility in how the system charge depletes there may exist an optimal solution to charge blend the rather than deplete all-electric.

3. Investigation of drive cycles versus control strategies, including:

    - Characterization of drive cycles to fit a particular control strategy

    - Control parameter optimization for specific drive cycles

4. Focus on real-time control system implementation, with the examination of issues such as:

    - Ideal control strategy versus safety overrides

    - Robust control design, failure modes, diagnostic actions.

    - Trade-off between developing an algorithm that requires no calibration, and the time it takes to develop this algorithm, versus developing an algorithm that takes little time to develop and a huge amount of time to calibrate; and,

    - Test algorithm in HIL test stand and finally in vehicle

5. Core teaching improvements on hybrid and electric control design could be offered. This program could include: low level controls and auto code generation, model-based-design, optimization of power train controls , and the tradeoffs between real world controls and optimization.

APPENDIX A:

Optimization Programming

The Program below is coded in Matlab 2010b. The purpose of this code is to understand the ideal operation of the powertrain components in a hybrid vehicle architecture and apply the learning's to a control strategy destined for use within a powertrain controller.

```
%Simple non-linear program for HEV fuel consumptions

function xopt = matlab_optimize(DriveCycle,PowerDemand,Title)
% simulation intialization
    tic;
    %clc;clear;
    load('optimize_init.mat')
    T=length(DriveCycle);
    dt=1;
    Nt= T/dt;
    assignin('base','dt',dt);
    assignin('base','Nt',Nt);
    SOC_init = 50;


    Voc = 330; %open circuit voltage
    Qmax = 40; %max battery amp-hrs
    %ESS_temp_index = evalin('base','ess.init.temp_index');
    %ESS_SOC_index = evalin('base','ess.init.soc_index');
    %ESS_Rint_dis = evalin('base','ess.init.rint_dis_map');
    %ESS_Rint_chg = evalin('base','ess.init.rint_chg_map');
    Rint = 0.07;

    fcs_pwr_index = evalin('base','fc.init.pwr_hot_index');
    fcs_h2_map = evalin('base','fc.init.h2_hot_map');


    %state power_fcs, power_batt, soc at each time step

    xlb = zeros(3*Nt,1);
    xub = zeros(3*Nt,1);

    % Bounds on power-fcs(watts lower and 93kw upper)
    xlb(1:3:end) = zeros(Nt,1); % Watts
    xub(1:3:end) = 93000*ones(Nt,1); % Watts

    % Bounds on power-batt (-50kw charge, 130kw discharge)
    xlb(2:3:end) = -50000*ones(Nt,1); % Watts
    xub(2:3:end) = 130000*ones(Nt,1); % Watts

    % Bounds on battery state-of-charge
    xlb(3:3:end) = 45;
    xub(3:3:end) = 55;

    % Equality constraints on power split (must meet demand)
    % P_fcs(t) + P_batt(t) = P_d(t)


    for t = 1:Nt
        Aeq(t, 3*(t-1)+1) = 1; % P_fcs
```

```
        Aeq(t, 3*(t-1)+2) = 1; % P_batt
        Aeq(t, 3*(t-1)+3) = 0;
    end

    beq = PowerDemand(1:Nt);

    x0(1:3:3*Nt,1) = zeros(Nt,1);
    x0(2:3:3*Nt,1) = beq(1:Nt);
    x0(3:3:3*Nt,1) = 50;


    f_cost=@(x)cost(x,dt,Nt,fcs_pwr_index,fcs_h2_map);
    f_const=@(x)constfun(x,dt,Nt,SOC_init,Rint,Qmax,Voc);

    options=optimset('Algorithm','Interior-
point','Display','iter','MaxFunEvals',1e7,'TolX',1e-5,'TolFun',1e-7,'TolCon',1e-
6,'LargeScale','on');

    [xopt,fval,output]=fmincon(f_cost,x0,[],[],Aeq,beq,xlb,xub,f_const,options);

    sum(DriveCycle(1:Nt))
    evalin('base','cost')

    fuel_economy_km_per_kg = sum(DriveCycle(1:Nt,2)*dt)/evalin('base','cost')

    %CREATEFIGURE(X1,YMATRIX1,Y1)
    %  X1:   vector of x data
    %  YMATRIX1:   matrix of y data
    %  Y1:   vector of y data
    X1=1:1:Nt;
    Y1=xopt(3:3:end);
    YMATRIX1(1,1:Nt)=xopt(2:3:end);
    YMATRIX1(2,1:Nt)=beq(1:1:end);
    YMATRIX1(3,1:Nt)=xopt(1:3:end);
    %  Auto-generated by MATLAB on 11-Oct-2010 12:38:57

    % Create figure
    figure1 = figure('InvertHardcopy','off','Color',[1 1 1]);

    % Create axes
    axes1 = axes('Parent',figure1,'YGrid','on');
    % Uncomment the following line to preserve the X-limits of the axes
    % xlim(axes1,[0 300]);
    % Uncomment the following line to preserve the Y-limits of the axes
    % ylim(axes1,[-40000 100000]);
    % Uncomment the following line to preserve the Z-limits of the axes
    % zlim(axes1,[-1 1]);
    box(axes1,'on');
    hold(axes1,'all');


    % Create multiple lines using matrix input to plot
    length(X1)
    length(YMATRIX1)
    plot1 = plot(X1,YMATRIX1,'Parent',axes1);
    set(plot1(1),'Color',[0 1 0],'DisplayName','Battery Power');
    set(plot1(2),'Color',[1 0 0],'DisplayName','Power Demand');
    set(plot1(3),'Color',[0 0 1],'DisplayName','FCS Power');




    % Create ylabel
    ylabel('Power(watts)','FontSize',12);
```

```matlab
    % Create xlabel
    xlabel('Time(s)','FontSize',12);

    % Create title
    title(Title,'FontSize',12);

    % Create axes
    axes2 = axes('Parent',figure1,'YAxisLocation','right',...
        'ColorOrder',[0 0.5 0;1 0 0;0 0.75 0.75;0.75 0 0.75;0.75 0.75 0;0.25 0.25 0.25;0 0
1],...
        'Color','none');
    % Uncomment the following line to preserve the X-limits of the axes
    % xlim(axes2,[0 300]);
    % Uncomment the following line to preserve the Y-limits of the axes
    % ylim(axes2,[49 52]);
    % Uncomment the following line to preserve the Z-limits of the axes
    % zlim(axes2,[-1 1]);
    hold(axes2,'all');

    % Create plot
    plot2=plot(X1,Y1,'Parent',axes2,'DisplayName','SOC');

    % Create ylabel
    ylabel('SOC(%)','VerticalAlignment','cap','FontSize',12);

    % Create legend
    legend1=legend([plot1(1);plot1(2);plot1(3);plot2],'Battery Power','Power Demand','FCS
Power','SOC','Location','NorthEast');
    set(legend1,'FontSize',12);

    fuelecon = sprintf('Fuel Economy (mpg) = %.2f \nFuel Economy (L/100Km) =
%.2f',fuel_economy_km_per_kg*.61,235.214583/(fuel_economy_km_per_kg*.61))


    % Create textbox
    annotation(figure1,'textbox',[0.15 0.8 0.25
0.1],'String',fuelecon,'FontSize',12,'FitBoxToText','on');

    % legend1 = legend([axes1;axes2],'show','show');
    % set(legend1,'location','NorthEast');

    %figure(1); clf; hold on;
    %plot(1:Nt, xopt(2:3:end),'g')
    %plot(1:Nt, beq(1:1:Nt), 'r')
    %plotyy(1:Nt, xopt(1:3:end),1:Nt,xopt(3:3:end))

    % text('Parent',axes1,['fuel economy(km/kg-h2) = ',num2str(fuel_economy_km_per_kg)]);
    % text('Parent',axes1,['fuel economy(mile/gal-gas) =
',num2str(fuel_economy_km_per_kg*.61)]);

    %ylabel('Power(watts)','FontSize',12)
    %xlabel('Time(s)','FontSize',12)
    %title('Power Split, green=Pbatt, blue=Pfcs, red=demand','FontSize',12)

    toc;
end

function [c,ceq]=constfun(x,dt,Nt,SOC_init,Rint,Qmax,Voc)

    %!!!!!since Rint_chg ~ Rint_dis at 40C and 50 SOC - set as constant 70mOhm.
    %below loop only necesary for variable resistance

    %for t = 1:Nt
```

```matlab
        %if x(2*Nt) >= 0;
            %discharge Rint
            %Rint(t) = interp2(ESS_SOC_index,ESS_temp_index,ESS_Rint_dis,40,50);
            %Rint(t)=0.0747;
        %else
            %Rint(t) = interp2(ESS_SOC_index,ESS_temp_index,ESS_Rint_chg,40,50);
            %Rint(t) = 0.0723;
        %end
    %end

%% current formulation

    % Vbatt = Voc - I*R
    % I = Pbatt/Vbatt
    % I = Pbatt/(Voc - I*R)
    %  I*(Voc-I*R) = Pbatt
    %  -R*I^2 + Voc*I - Pbatt = 0
    %  R*I^2 - Voc*I + Pbatt = 0
    %  I = [Voc +/- sqrt(Voc^2-4*R*Pbatt)]/(2*R)
    %  ex 40kw discharge
    %  [330 +/- (330^2 - 4*0.120*40000)]/(2*R) = [330 +/- 299]/2R
    %  therefore has to be negative in both cases (charge or discharge) for realistic I
    %  positive in the formula would cause pack melt down (>10^3 amps)
%%
    % I(1:Nt) = (-Voc - sqrt(Voc^2 - 4*Rint(1:Nt)*x(2:2:end)))/(2*Rint(1:Nt));
    %for t= 1:Nt
        % I(t)= (Voc - sqrt(Voc^2 - 4*Rint*x(3*(t-1)+2)))/(2*Rint);
    %end

    %40 amp-hours max charge
    %non-linear inequalities
    %SOC must be greater than 50 (net gain)

%% Non-Lin inequalities
    c = 50 - x(end);

%% non-linear equalities

    %SOC(t)=SOC(t-1)-I*dt/3600/Qmax*100
    for t=1:Nt-1
        ceq(t)= x(3*t+3)-x(3*t)+(Voc - sqrt(Voc^2 - 4*Rint*x(3*(t-
1)+2)))/(2*Rint)*dt/3600/Qmax*100 ;
    end

    %set initial soc to soc_init
    ceq(Nt)= SOC_init - x(3);

end


function cost = cost(x,dt,Nt,fcs_pwr_index,fcs_h2_map)



    %h2 fuel consumption=f(power fcs) linear interpolation


    mdot_h2(1:Nt) = interp1(fcs_pwr_index,fcs_h2_map, x(1:3:end));

    %total fuel consumption over the drive cycle in grams
    cost = sum(dt*mdot_h2);
    assignin('base','cost',cost);
```

```
end
```

Variables used:

Name	Size	Bytes	Class Attributes
DC_Power_Demand_HWY	766x1	6128	double
DC_Power_Demand_HWY_30regen	766x1	6128	double
DC_Power_Demand_HWY_noregen	766x1	6128	double
DC_Power_Demand_UDDS	1371x1	10968	double
DC_Power_Demand_UDDS_30regen	1371x1	10968	double
DC_Power_Demand_UDDS_noregen	1371x1	10968	double
DC_Power_Demand_US06	601x1	4808	double
DC_Power_Demand_US06_30regen	601x1	4808	double
DC_Power_Demand_US06_noregen	601x1	4808	double
ESS_max_charge	601x1	4808	double
ESS_max_discharge	601x1	4808	double
ESS_net_energy	766x1	6128	double
ESS_soc	766x1	6128	double
Nt	1x1	8	double
ambient	1x1	132	struct
ans	1x1	8	double
chas	1x1	1040	struct
cost	1x1	8	double

dcdc	1x1	396	struct
drv	1x1	6104	struct
dt	1x1	8	double
ess	1x1	15996	struct
fc	1x1	12684	struct
fuel_consumed	766x1	6128	double
hcs	1x1	132	struct
mc	1x1	112208	struct
mc1	1x1	155704	struct
mc2	1x1	110436	struct
power_batt	601x1	4808	double
power_fcs	601x1	4808	double
rms_UDDS_30regen	1x1	8	double
rms_UDDS_noregen	1x1	8	double
rms_US06_30regen	1x1	8	double
rms_US06_noregen	1x1	8	double
rms_hwy_30regen	1x1	8	double
rms_hwy_no_regen	1x1	8	double
rms_hwy_noregen	1x1	8	double
sch_cycle_hwy	765x2	12240	double
sch_cycle_udds	1370x2	21920	double
sch_cycle_us06	601x2	9616	double
sch_grade	2x2	32	double
sch_key_on	2x2	32	double

sch_metadata	1x1	136	struct
t	1x1	8	double
tout	766x1	6128	double
trans	1x1	15720	struct
veh	1x1	380	struct

APPENDIX B: Detailed Figures

Instantaneous
Power/Torque Control

$T_{F,meas}$

Front Motor Controller
- black box torque PID

Front Motor Inverter

Front Motor Drive Unit

$T_{F,req}$

$P_{F,meas}$

$P_{FCS,req}$

FCS Control

FCS

P_{FC}

Vehicle Chassis
- Wheels
- Mass
- Aerodynamics
- Friction
- Dynamics

Pedals
PRNDL
CSMode
RegenON

Driver

Torque Decider
-torque magnitude
-torque direction
-torque split

T

Hybrid Controller
- Power Split
- DCDC Power Request
- FCS Power Request

Battery Management System (BMS)

Battery

HV Electrical Loads

$P_{DCDC,req}$

DC/DC Control

DC/DC

P_{DCDC}

$P_{R,meas}$

$T_{R,req}$

Rear Motor Controller
- Black box torque PID

Rear Motor Inverter

Rear Motor Drive Unit

$T_{R,meas.}$

Vehicle Response

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