A Plug-in Hybrid Electric Vehicle Loss Model to Compare Well-to-Wheel Energy Use from Multiple Sources

Kurt M. Johnson

Thesis submitted to the faculty of Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
in
Mechanical Engineering

Committee:
Dr. Douglas J. Nelson
Dr. Michael W. Ellis
Dr. Charles F. Reinholtz

July 7, 2008
Blacksburg, VA

A Plug-in Hybrid Electric Vehicle Loss Model to Compare Well-to-Wheel Energy Use From Multiple Sources

Kurt M. Johnson

Abstract

Hybrid electric vehicles (HEV) come in many sizes and degrees of hybridization. Mild hybrid systems, where a simple idle stop strategy is employed, eliminate fuel use for idling. Multiple motor hybrid systems with complex electrically continuously variable transmissions in passenger cars, SUVs and light duty trucks have large increases in fuel economy. The plug-in hybrid electric vehicle (PHEV) takes the electrification of the automobile one step further than the HEV by increasing the battery energy capacity. The additional capacity of the battery is used to propel the vehicle without using onboard fuel energy. Commercial software of great complexity and limited availability is often used with sophisticated models to simulate powertrain operation. A simple method of evaluating technologies, component sizes, and alternative fuels is the goal of the model presented here. The objective of this paper is to define a PHEV model for use in the EcoCAR competition series. E85, gaseous hydrogen, and grid electricity are considered. The powertrain architecture selected is a series plug-in hybrid electric vehicle (SPHEV). The energy for charge sustaining operation is converted from fuel in an auxiliary power unit (APU). Compressed hydrogen gas is converted to electricity via the use of a fuel cell system and boost converter. For E85, the APU is an engine coupled to a generator. The results of modeling the vehicle allow for the comparison of the new architecture to the stock vehicle. In combination with the GREET model developed by Argonne National Lab, the multiple energy sources are compared for well to wheel energy use, petroleum energy use, and greenhouse gas emissions.

Acknowledgements

I would like to acknowledge Dr. Doug Nelson, Ryan Pawlowski, Michael Diaz, and the students of the Hybrid Electric Vehicle Team for their contributions.

Table of Contents

List of Multimedia Objects

Tables

Figures

Equations

Abbreviations

AER	All Electric Range
ANL	Argonne National Lab
AT	Advanced Technology
AVTC	Advanced Vehicle Technology Competitions
BEV	Battery Electric Vehicle
BMF	Battery Model Function
CARB	California Air Resources Board
CD	Charge Depleting
CDH	Charge Depleting Hybrid
CDTS	Competition Design Target Specifications
CI	Compression Ignition
CO2	Carbon dioxide
CS	Charge Sustaining
CSF	Control Strategy Function
DC	Direct Current
DoE	Department of Energy
E85	85% Ethanol 15% Gasoline fuel blend
EGF	Engine Generator Function
EVS	Electric Vehicle Symposium
FTP	Federal Test Procedure
GH2	Gaseous Hydrogen
GHG	Greenhouse gas
GM	General Motors Corporation
GREET	Greenhouse gas, Regulated Emissions, and Energy use in Transportation
GVWR	Gross Vehicle Weight Rating
HEV	Hybrid Electric Vehicle
HEVT	Hybrid Electric Vehicle Team of Virginia Tech
HPPC	Hybrid Pulse Power Characterization
HWFET	Highway Fuel Economy Test
ICE	Internal Combustion Engine
kJ	kiloJoules
km	kilometers
kph	kilometers per hour
kW	kilowatts
kWh	kilowatt-hours
MCF	Motor Controller Function
mi	miles
mpgge	miles per gallon gasoline equivalent
mph	miles per hour
NHTS	National Highway Transportation Survey
Nm	Newton-meters
NOx	Oxides of Nitrogen
NREL	National Renewable Energy Lab
PHEV	Plug-in Hybrid Electric Vehicle

PSAT	Powertrain System Analysis Toolkit
PTW	Pump to Wheels
PZEV	Partial Zero Emission Vehicle
RFG	Reformulated Gasoline
RFP	Request for Proposal
s	seconds
SI	Spark Ignited
SOC	State of Charge
SOx	Oxides of Sulfur
SPHA	Series Plug-in Hybrid Architecture
SPHEV	Series Plug-in Hybrid Electric Vehicle
UDDS	Urban Dynamometer Drive Schedule
UF	Utility Factor
US06	Supplemental FTP aggressive drive cycle
USABC	U.S. Advanced Battery Consortium
VMT	Vehicle Miles Travelled
VOC	Volatile Organic Compounds
WTP	Well to Pump
WTT	Well to Tank
ZEV	Zero Emissions Vehicle

1. Introduction

The primary energy source for transportation in the United States is petroleum. Fossil resources are extracted from the earth and are non-renewable. The use of fossil fuels releases tons of carbon dioxide (CO2) and other greenhouse gasses (GHG) into the atmosphere every day. The United States imported more than 65% of the petroleum it uses as of March 2008 [1]. This amounts to billions of dollars leaving the country's economy. The use of petroleum for transportation is no longer sensible from an environmental or economic position. Bob Lutz, General Motor's Vice Chairman of Global Product Development, states [2], "The biggest way to get huge gains in reducing petroleum consumption is through electrification." The introduction of the hybrid electric vehicle (HEV) to the U.S. market opened the door for advanced technology vehicles to use electric powertrains to reduce petroleum consumption by increasing fuel economy. HEVs increase fuel economy by decreasing the size of the engine, which allows the engine to operate in a higher efficiency region. The addition of electric components such as motors, batteries, and DC/DC converters allows for modification of powertrain operation. HEVs come in many sizes and degrees of hybridization, from mild hybrid systems, where a simple idle stop strategy is employed, eliminating fuel use for idling, to multiple motor hybrid systems with electrically continuously variable transmissions in passenger cars, SUVs and light duty trucks. Figure 1 further illustrates the energy efficiency potential of the electrification of the automobile [3].

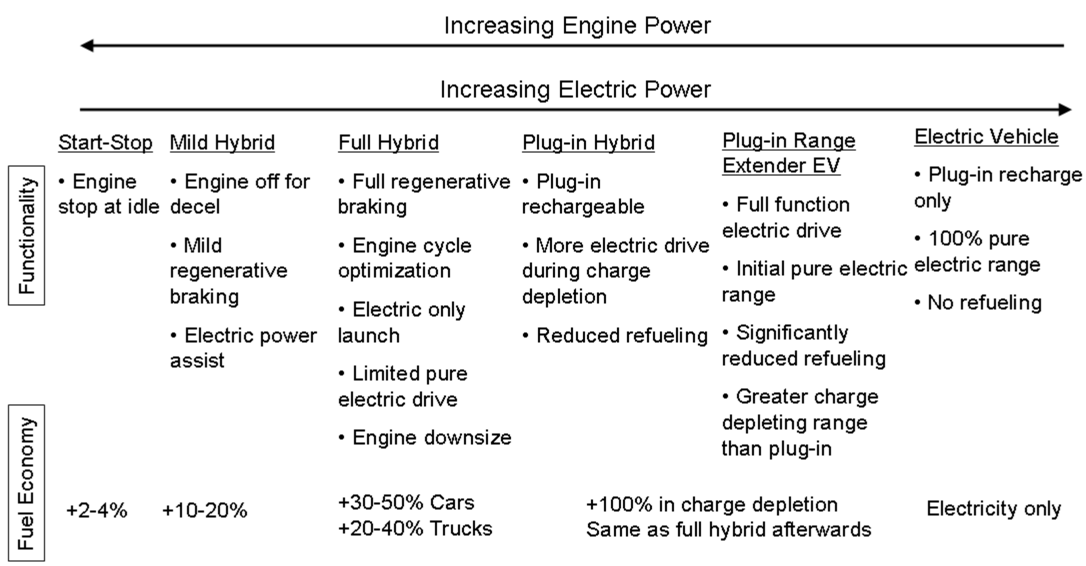

Figure 1. Hybridization and fuel economy potential for varying degrees of hybridization [3].

The Hyrbid Electric Vehicle Team (HEVT) of Virginia Tech has modeled a plug-in hybrid electric vehicle (PHEV) in response to a request for proposal (RFP) for admission into the Advanced Vehicle Technology Competition (AVTC) series "EcoCAR: The NeXt

Challenge," sponsored by the U.S. Department of Energy (DoE) and General Motors Corporation (GM).

The series plug-in hybrid electric vehicle (SPHEV), shown in Figure 2, takes the electrification of the automobile one step further than the HEV by increasing the battery size. The additional capacity of the battery is used to propel the vehicle without using fuel energy. In contrast, the battery in an HEV is sized for power and does not store a large enough quantity of energy to propel the vehicle a significant distance. This all electric range (AER) uses grid electricity as its energy source, allowing for the use of non-petroleum energy sources for transportation.

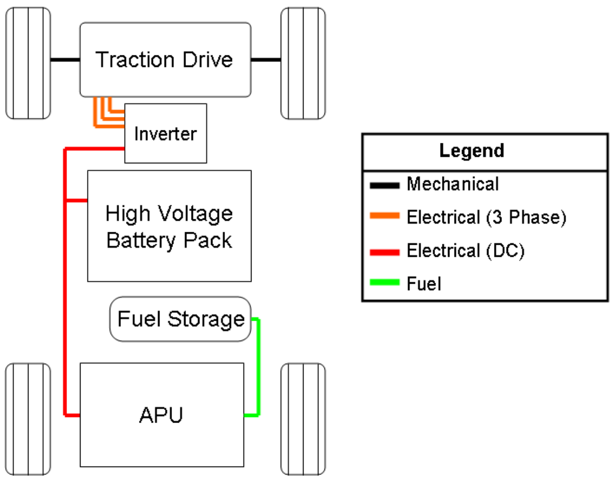

Figure 2. Series plug-in hybrid architecture diagram.

The objective of this thesis is to define a vehicle model for use in the EcoCAR competition series which calculates energy use based on component losses. The model of the series plug-in hybrid electric architecture (SPHA) allows for the comparison of the hybrid architecture to the stock vehicle's well-to-wheel energy use, petroleum energy use, and greenhouse gas emissions. The results of the comparison highlight the strengths and weaknesses of the SPHA.

Section 2 provides a review of relevant publications that focus on plug-in hybrid operational modes, battery systems, and environmental impact. Section 3 details the EcoCAR competition, stock vehicle, and SPHA model. The operational modes and upstream energy use analysis are presented in Section 4. The SPHA energy use is presented in Section 5. The well-to-wheel analysis for energy use and emissions is discussed in Section 6 and finally, concluding remarks are given.

2. Literature Review

2.1 PHEV Operational Modes and Battery Sizing

A paper from the National Renewable Energy Laboratory (NREL), General Motors Corp. and the U.S. Department of Energy (DoE) [4] covers battery requirements developed in support of the U.S. Advanced Battery Consortium (USABC). The authors outline their work in vehicle platform definition, performance goals, and the operating method to achieve electric range goals. This aligns closely with the purpose of the SPHA hybrid architecture, but focuses primarily on battery sizing. The authors also outline some barriers to plug-in hybrid commercialization as well as the benefits and drawbacks of a plug-ins.

2.1.1 Mode Definition

The operating modes and terminology of a plug-in hybrid are well defined. Charge depleting (CD) operation occurs when the state of charge (SOC) of the energy storage device decreases over time. In charge sustaining (CS) operation, while the SOC will vary, the trend is to stay the same. Most commercially available hybrids operate as CS hybrids. The all electric range (AER) is defined as the distance driven before the first engine start after the energy storage device is full charged. Blended operation, also known as charge depleting hybrid (CDH) mode, decreases SOC similarly to CD operation, but allows for engine use for power requests beyond what the energy storage device is able to support. For the length of the AER, the vehicle is in CD mode and can be classified as a zero emission vehicle (ZEV) since there are no tailpipe emissions.

The advantages and disadvantages of using fully electric versus blended operation for CD mode are discussed. The fully electric CD mode allows for a larger displacement of petroleum based fuels as well as a reduction of vehicle emissions, but they require an energy storage device that is more prohibitive to commercialization based on its size and cost. After setting vehicle performance parameters and defining vehicle parameters, iterations were made using Powertrain System Analysis Toolkit (PSAT) to simulate vehicle operation. One finding that was significant to the SPHA design decision is that "The electric energy consumption for propelling the vehicle a given distance over the UDDS drive cycle (Wh/mile) does not significantly depend on whether operation is all-electric or blended" [4]. This finding justifies the selection of a fully electric powertrain for CD operation, given the benefits in petroleum consumption and emissions.

2.1.2 Simulation Results and Recommendations

The discussion moves to discuss the energy use of the simulated vehicle platforms. The modeling of a midsize passenger car was not useful for the SPHA modeling, as the authors modeled a vehicle significantly lighter than the SPHEV. It is easiest to compare the SPHEV to a midsize crossover utility vehicle as the mass of this vehicle is closer than the midsize passenger car. A set of battery requirements for PHEVs is recommended in two different range categories suggesting the high power to energy battery meet these standards in 2012, and the higher energy to power battery in 2016.

2.2 Battery Test Modifications for PHEVs

The paper "Plug-in Hybrid Vehicle Testing Procedures" from Idaho National Lab [5] focuses on the changes to battery testing required for the new set of goals for plug-in hybrid vehicle batteries by DoE and USABC. DoE pursues automotive research with manufacturers through the FreedomCAR collaboration. FreedomCAR has produced battery goals and test procedures for plug-in hybrid vehicle battery systems for 10 mile and 40 mile all electric range. Some of the tests outlined in the FreedomCAR Battery Test manual have been changed for use on plug-in batteries. An example of this is the static capacity test, which uses a constant current down to the minimum voltage. It has been modified to become the constant power test, which draws a constant power down to the minimum voltage. The hybrid pulse power characterization (HPPC) test determines the available energy and power in CS mode and the available energy in CD mode. It also allows for the evaluation of resistance degradation for life cycle testing. These tests also contribute data for the construction of battery performance models for use in simulation.

The results of the HPPC test indicate a relatively constant resistance (both charge and discharge) of 0.0014 to 0.0016 Ohms from 0 to 90% discharged for each cell. This allowed a selection of a reasonably conservative resistance in building the SPHA model. From the HPPC, a CS available energy at a 10 kW discharge rate is calculated. This allows the construction of a power to energy removed plot which shows the available power per cell for discharge and regen after energy has been removed. By changing the operating voltage limits of a pack, the usable energy range is known and able to be varied. The difference between the discharge and regen curves is the available CS energy. The plug-in does not have to meet the minimum regen power goals set by FreedomCAR during CD operation. This allows an extension of the operating range beyond the CS zone and further increases the energy available to operate the vehicle. With a minor change to the set procedure and changes to the analysis methods, a single test can provide both the CS and CD available energies.

2.3 Thesis on Electric Powertrains

Kromer's thesis titled "Electric Powertrains Opportunities and Challenges in the US Light-Duty Vehicle Fleet" studies many aspects of personal transportation [6]. After describing the simulations and vehicle characteristics, the author discusses the well-to-tank (WTT) energy use and greenhouse gas (GHG) emissions. Battery technology is discussed, followed by the examination and simulation of spark ignited (SI), compression ignition (CI), and hybrid powertrains. Plug-in, full battery electric and fuel cell architectures are also examined.

2.3.1 The Plug-in Hybrid Electric Vehicle

Of particular interest, plug-in hybrids are defined as vehicles having the ability to recharge from the grid. The electric driving range is in the tens of miles, after which, an

ICE powered by gasoline is used to power the vehicle. "The PHEV offers a compromise between the drivability and affordability of the hybrid-electric vehicle, and the potential environmental and energy security benefits of the battery-electric vehicle (BEV)" [6]. The author continues the discussion of plug-ins with definitions of operational modes and design parameters.

2.3.2 Electric Range

The vague term, electric range, is dependant upon many factors including the drive cycle and the available electric energy from the battery. The use of an engine during CD mode will extend the range for CD operation and allow for a smaller electric powertrain when coupled in a parallel hybrid. The evaluation of electric range is carried out over an average of the federal test procedure (FTP), the highway fuel economy test (HWFET) and the US06 drive cycles and does not include battery energy outside the envelope of usable SOC. Given this usable SOC envelope, the electric range is equated to an energy use. The use of a utility factor to determine the amount of petroleum displaced is described.

2.3.3 Hybridization Ratio

The paper moves forward to discuss the authors limitations on powertrain size, which is referred to as the hybridization ratio. The use of an all electric powertrain to meet driver demand is cost prohibitive. The battery system costs more the more energy it can store. The more power both the battery and motor deliver, the more the cost is increased. Since the plug-in design uses a parallel architecture, so that both electric and ICE power can power the vehicle simultaneously, a concern arises as to the drivability of the vehicle in all electric mode. The available power will not be as great, so the electric system must be sized to meet all acceleration goals, again impacting cost. The benefit of having fewer cold starts of the engine and a greater impact on petroleum energy use are both arguments that can be made for having a full electric drive.

Simulations were performed in ADVISOR using multiple motor and ICE sizes from the minimum electric drive size needed to meet the US06 drive trace down to the minimum electric drive size for full regenerative brake energy capture. The simulations show that on the US06 drive cycle the higher the degree of hybridization (DOH), which is the peak electric power relative to the whole powertrain power, the less fuel is consumed. Therefore, the fully electric vehicle consumed the least amount of fuel in CD mode, even with a slight weight penalty for the additional mass of the larger components. The CS mode fuel consumption of the fully electric capable vehicle continues to stay below the blended vehicles, though they do converge over a long enough distance (>150 mi).

Before concluding the section on PHEVs, the author addresses grid electricity production and the uncertainty of how the mix of power generation of the grid in the future will affect GHG emissions and energy consumption. The result of the simulations and analysis indicate that the PHEV does not compete in the short term with the HEV unless petroleum displacement is of principal interest. In the long term, PHEVs offer the capability to exceed the HEV in petroleum use and GHG emission reductions.

2.4 Environmental Impact of PHEVs

This paper from EPRI and NRDC address the concern about the environmental impact of the PHEV and were presented at the 23rd Electric Vehicle Symposium (EVS) [7]. The paper summarizes the results of a study on the impact of electrifying transportation on transportation and power generation emissions. One element of emissions not touched on by previously reviewed papers is the reduction of emissions due to vehicle refueling. The study assumes a rapid market penetration of vehicles by the year 2030 with approximately 40% of the national fleet charging from the grid and compares this to a zero market share of PHEVs. The model is run assuming a gradual penetration of PHEVs in the market, the power generation sector is incrementally loaded as market share increases, and emissions meet current federal standards. Air quality is monitored as a function of transportation and power generation sector outputs. Carbon emissions are not considered for this study to remain consistent with AEO 2006.

As a result of PHEV incorporation into the fleet at a high market penetration, the overall air quality increases. Vehicle side criteria emissions decrease, as fuel energy is displaced by electrical energy. Power plant oxides of sulfur (SOx) emissions are capped by law and do not increase. Oxides of nitrogen (NOx) and particulate matter (PM) emissions from powerplants increase. The NOx emissions are offset by a dramatic decrease in transportation sector emissions.

2.5 Battery Technology Report

The DoE Office of Energy Efficiency and Renewable Energy issued the 2006 report titled "Energy Storage Research and Development" [8]. The office centers its efforts on battery technology development, applied battery research, and long-term exploratory research. A portion of the applied battery research deals with cost reduction.

The advanced technology development battery research program focuses on the following barriers for lithium based battery technology in its entrance to the market: calendar life, operating temperature, cost per kW, sufficient durability for in vehicle use. In testing alternative materials for lithium based battery negative electrode, new materials were identified showing high power capability, good reactivity, and long life. In long term research, development is continuing in stable, low cost lithium based battery materials. Despite their current high cost and fragile nature, lithium based battery technology is still improving and the selection of such a battery for a PHEV based on low mass and high energy density when compared to other technologies is justified.

2.6 Energy Storage System Design

The publication [9] documents an approach to PHEV modeling for energy storage system design. An analysis of the current vehicle fleet and vehicle miles travelled (VMT) growth suggests that if all vehicles sold in 2011 and beyond were petroleum fueled hybrids, petroleum consumption 10 years in the future would still be greater than today and would never drop below current petroleum use in the future. The issue at hand is to displace as much petroleum as possible, while sustaining tolerable levels of cost increase. Biofuels are mentioned as a potential petroleum displacing technology. PHEVs are proposed as an option for further petroleum displacement, given their multiple energy source capability.

2.6.1 Energy Storage System

Specifying the power, energy, and usable SOC window determine many other factors of the battery and vehicle. Based on daily VMT statistics, a PHEV capable of 20 miles of AER operation would use electricity instead of petroleum for 30% of its operation. This represents 5-10 times more energy available in the energy storage system than current hybrid designs. Battery chemistry also affects the mass, stored energy, available power and power to energy ratio (P/E). Lithium ion technology has higher ratio of specific power (W/kg) to P/E than does nickel metal hydride technology allowing for lighter, higher power systems using the lithium technology. Lithium ion battery systems also have a higher power density (W/L) to P/E ratio yielding smaller systems and facilitating easier packaging.

To achieve the maximum in charge sustaining fuel economy, it is desirable to downsize the engine to only provide steady state power. The peak steady state power will either be determined by the continuous top speed or by a gradeability requirement, which ever is greater. Low power energy storage systems allow for a decrease in cost, mass and volume of the energy storage system while still providing some degree of AER. This could be used in light load urban driving and is similar to the CDH powertrain described in section 2.1.

The high incremental cost of the high power PHEV energy storage system is a barrier to commercialization. The low power energy storage system, while providing the same amount of energy, realizes a lower cost with a 6% penalty in petroleum consumption. Using an AER strategy as opposed to a blended sees an increase in average engine and battery efficiency, but a decrease in motor efficiency. The engine increase is due to its smaller size and higher loading. The battery would have to be a higher power to energy ratio to use an AER strategy, giving a battery with lower internal resistance and fewer losses. The motor used in a blended strategy would be smaller and at a higher load fraction, slightly increasing its average efficiency. The combinations of motor, engine and battery sizing provides a design space that can be optimized for a particular goal, whether it be petroleum displacement or cost reduction.

2.7 PHEV with Lithium-ion Battery Modeling

This report documents the efforts of Argonne National Lab (ANL) to simulate the operation of a PHEV with a lithium ion battery [10]. Two mass classes, mid-sized passenger vehicle and mid-sized SUV, were used along with six different AERs ranging from 10 to 60 miles. Researchers used the ANL developed PSAT to create and evaluate the vehicle model. Post-processing was done to determined battery load characteristics as well as peak operation points. Simulation of PHEV battery charge and discharge resistance is more difficult in PHEVs due to a charge or discharge cycle that potentially lasts for several minutes.

Component sizing for a PHEV also adds a level of complexity beyond HEV modeling due to having three degrees of freedom, engine size, motor size and battery size, whereas the HEV model only includes the first two since battery energy does not greatly impact performance, only battery life. A flow chart process was used to automate the component sizing process. The flow chart starts by sizing the motor for UDDS peak power. The battery power is then sized to meet the motor electrical demand. The engine power is then selected to meet performance goals. Lastly the battery energy requirement is set to meet AER goals. Extra battery energy is added to allow for loss of energy as the battery ages. This method of powertrain component selection allows for electric operation only during mild driving and is equivalent to blended or CDH powertrains from previous papers. The analysis only presents vehicle results from the UDDS drive cycle.

2.7.1 Results

The trends for both the midsize passenger vehicle and SUV were similar due to control strategy and powertrain similarities. As would be expected, a longer AER yielded mass increases in the battery pack, which required more energy, which increases the size of other components as well. The battery size increased nearly linearly from 7.5 to 60 mile AER due to the lithium chemistry of the battery packs. Even with an AER of 60 miles, the battery pack mass was only 16% of total vehicle weight for the passenger car, and 17% for the SUV.

The powertrain operates efficiently in CD mode. This efficient powertrain reduces the sensitivity of the vehicle's energy use to changes in mass. This low sensitivity results in a less than 16% increase in energy consumption for the passenger vehicle. The energy use per mile is a linear function of AER. Since the battery power is held nearly constant for increasing AER, the P/E ratio varies hyperbolically.

The electric machine power is almost constant, increasing only slightly as battery mass increases with AER. Few points on the UDDS require more than 35 kW of motor power for the SUV while the passenger vehicle needs only 25 kW to meet 90% of UDDS demand.

2.8 Boyd Battery Paper

Most commercial grade vehicle simulation suites require detailed knowledge of the components that go into the model. An alternative method presented in this paper is the simplification of the vehicle model resulting in the analysis of vehicle classes [11]. The work presented is for a simplified battery model that allows for design or sizing studies and doesn't require the detailed inputs of the more complex models. Table 1 displays the inputs and outputs of the model. The model allows for the use of temperature corrections for state of charge, but does not require it for loss calculations, since the charge and discharge resistance are constants. To make the model more robust, the two resistances could be functions of temperature and SOC. The model is within 5% of measured current from collected data up to about 100 amps, above which, measured current is lower than model current. The model provides a conservative estimate of battery energy used and correctly models the battery losses.

Table 1. Boyd battery model inputs and outputs.

Parameter	**Variable**	**Units**
Required Input:		
Power	*P*	Watts
Open Circuit Voltage	*Voc*	Volts
Charge Resistance	*Rchrg*	Ohms
Discharge Resistance	*Rdis*	Ohms
Pack Energy Capacity	*E*	Watt-hours
Initial State of Charge	*SOCinit*	%
Thermal Resistance	*1/UA*	°C /Watt
Thermal Capacity	*mCp*	Joules/°C
Ambient Temperature	*Tamb*	°C
Initial Battery Temp.	*Tinit*	°C
Output:		
Battery Current	*I*	Amps
Battery Voltage	*V*	Volts
Power Loss	*Ploss*	Watts
Internal Battery Power	*Pint*	Watts
Internal Battery Energy	*Eint*	Watt-hours
State of Charge	*SOC*	%
Battery Temperature	*T*	°C

2.9 Summary of Literature Review

The papers above are examples of the research being done with PHEVs. The battery system provides the largest hurdle to PHEV adoption in the marketplace, and much research is being done along those lines. Current battery research is concentrated on the chemistry of battery cells. The literature reviewed discusses the improvements that lithium-ion technology brings over the current nickel metal-hydride batteries in terms of available power and energy for a given weight and volume. These batteries will have to undergo more rigorous testing for acceptance in PHEVs. This change in test procedures suggests that PHEVs will require different performance from their batteries. Despite the superior performance, lithium based battery systems are less forgiving than other technologies and require more monitoring to prevent failure. Research is continuing on low cost lithium technologies for their low mass and high energy density. Battery system cost is the major barrier to commercialization of the PHEV. Only the environmental impact due to vehicle or upstream emissions are discussed, and not battery production. Air quality will improve with adoption of PHEVs.

PHEVs and aspects of their simulation and characterization are also discussed in the literature review. The major discrepancy between the papers is the use of varying calculations for AER. Some tests include city and highway drive cycles while others focus on city drive cycles only. All address the differences between charge depleting and charge sustaining operation. Each paper considers an option for blended operation as well. The cost of a full electric drive with an onboard fuel converter is presented as a hindrance to commercialization, but the benefits of fewer cold starts and a greater petroleum impact are arguments for adoption.

The analysis focuses on petroleum consumption reduction, but only as far as the powertrain improves fuel economy or displaces petroleum by use of grid electricity alone. Commercial software of great complexity and limited availability, such as PSAT, is often used with sophisticated models to provide powertrain simulation. A simple method of evaluating technologies, component sizes, and alternative fuels is lacking. This paper will present such a model suitable for student vehicle competition technology selection and component sizing. The next section outlines the next in a series of student vehicle competitions by the U.S. DoE, vehicle characteristics, the model, and component sizing.

3. Series Plug-in Hybrid Architecture

3.1 Introduction to the EcoCAR Competition

The EcoCAR: The NeXt Challenge (EcoCAR) competition is the latest in the US Department of Energy (DoE) sponsored advanced vehicle technology competitions. A three year competition, EcoCAR is designed to challenge students to reengineer a GM vehicle for improved fuel economy and reduced emissions while maintaining performance and consumer features [12]. Unlike previous DoE AVTCs, EcoCAR is designed to address the California Air Resources Board (CARB) ZEV regulations [15]. To select schools, the organizing body of EcoCAR, Argonne National Lab has issued a request for proposal (RFP) and invited universities to submit designs for consideration. The RFP outlines specific vehicle properties for use in the design simulations. Table 2 displays the RFP vehicle properties [13].

Table 2. Vehicle properties supplied in the EcoCAR RFP.

EcoCAR Vehicle Properties	
Vehicle Test Mass	1705 kg
Gross Vehicle Weight Rating	2141 kg
Road Load Coefficients	F0 = 93.45 N
	F1 = 3.58 N/(m/s)
	F2 = 0.42 N/(m/s)2
Cd	0.33
Af	2.209 m2
Crr	0.0056

The universities were first asked to complete a modeling exercise to determine the road load and energy use at the wheels of a vehicle based on the given vehicle properties. Using this information, the universities were asked to submit a design for a hybrid electric vehicle with electric drive power not to exceed 50 kW. The design must meet the EcoCAR targets for top speed, acceleration, fuel economy, etc. These specifications are outlined in Table 3. The final exercise requested in the RFP is the submission of a design of the university's choosing that must also meet the specifications outlined in Table 3 and explain the reasoning in fuel or energy carrier choice. In addition to the goals set forth by the EcoCAR RFP, Virginia Tech's goals were to greatly impact petroleum use, have a 0-100 kph acceleration time of 10 s, and have an all electric range of 65 km (40 mi). These specifications are referred to as the competition design target specifications (CDTS).

Table 3. EcoCAR designs targets for modeled vehicles.

Performance/Utility Category	EcoCAR: The NeXt Challenge Proposal Design Targets
Fuel Consumption (unadjusted state of charge-corrected miles per gallon gasoline equivalent [mpgge] on FTP City and Highway Cycles)	27.5 to 38.5 mpgge City 37.5 to 57.5 mpgge Highway
GHG Emissions	176 to 356 CO2 equivalent g/mi
Interior Size/ Number of Passengers	4 Passenger
Luggage Capacity	Equal to stock vehicle ~ 425 L (15 cu ft)
Minimum Range (on FTP City and Highway Cycles)	327 km (200 mi) – 330 km*
0-100 kph Acceleration Time, s	12 s (10 s)*
Top Speed	145 kph (90 mph)
All Electric Range*	65 km (40 mi)

*HEVT specified

The design of the university's choosing must fall into one of four categories based on the CARB ZEV requirements. The four categories supported by the competition are:

- ☐ Hybrid electric vehicle - <50 kW peak electric drive power
- ☐ Hybrid electric vehicle - >50 kW peak electric drive power
- ☐ Range extending and full function electric vehicles
- ☐ Hydrogen fuel cell vehicles

The CARB vehicle types that correspond to these categories are type D, E, II, and III [13]. Table 4 outlines the different CARB categories for advanced technology (AT) partial zero emission vehicles (PZEVs). Table 5 defines ZEV categories from CARB. In addition to these four vehicle categories, both charge sustaining and charge depleting versions are allowed.

Table 4. CARB AT PZEV vehicle characteristics [14].

Characteristics	Type A	Type B	Type C	Type D	Type E
Electric Drive System Peak Power Output	>= 4 kW	>= 4 kW <10 kW	>= 10 kW	>= 10 kW	>= 50 kW
Traction Drive System Voltage	< 60 Volts	>= 60 Volts	< 60 Volts	>= 60 Volts	>= 60 Volts
Traction Drive Boost	Yes	Yes	Yes	Yes	Yes
Regenerative Braking	Yes	Yes	Yes	Yes	Yes
Idle Start/Stop	Yes	Yes	Yes	Yes	Yes

Table 5. CARB ZEV vehicle definitions [14].

ZEV Tier	Common Description	UDDS ZEV Range	Fast Refueling Capability
NEV	NEV	No minimum	N/A
Type 0	Utility EV	<50 miles	N/A
Type I	City EV	>=50 & <100 miles	N/A
Type II	Full Function EV	>=100 miles	N/A
Type III	Fuel Cell EV	>=100 miles	Must be capable of replacing 95% maximum rated energy capacity in <= 10 minutes

3.2 SPHA Design Motivation and Process

As part of the EcoCAR RFP process, the Hybrid Electric Vehicle Team of Virginia Tech (HEVT) completed the steps to model the given vehicle's road load and energy use, designed a vehicle with below 50 kW of electric drive power, and a vehicle design of the university's choosing that meets the CDTS. By limiting the power of the electric drive system to less than 50 kW for the second part of the modeling exercise, the EcoCAR organizers eliminated the possibility of pure electric drive vehicles, since a 50 kW drive system would be unable to meet the competition target design specifications. This eliminates Type II and III ZEVs as well as Type E hybrids, leaving only Type D vehicles. HEVT moved into the third part of the modeling exercise looking at the three types of vehicles that were unavailable in the second part.

The process of selecting a vehicle architecture started with a review of available architectures, team experience, competition allowable energy carriers, and technologies for improving the energy and petroleum use of the stock vehicle. Based on the desire to have an all electric range of 40 miles, HEVT selected an all electric drivetrain, allowing a large battery to provide peak power to the vehicle during the charge depleting operational mode, with a series fuel converter supplying additional range for charge sustaining operation. The fuel converter and associated electric machines, electronics, and subsystems are known as the auxiliary power unit (APU). The battery pack will provide enough power to allow for full performance in charge depleting mode without utilizing power from the APU, so the SPHEV does not use a blended CD mode.

3.3 Modeling the Baseline Vehicle

The vehicle characteristics supplied by the EcoCAR organizers are shown in Table 3. The vehicle modeled by these properties is a 2008 Chevrolet Malibu. General Malibu vehicle properties are shown in Table 6.

Table 6. Vehicle specifications for the stock Malibu [15].

Malibu Vehicle Specifications	
Vehicle	5 passenger car
Engine	2.4L L4, 175 hp (130 kW),
Transmission	4 spd automatic with FWD
Test Mass	3750 lb (1700 kg)
GVWR	4720 lb (2141 kg)
Fuel Economy (EPA unadjusted)	City: 27.3 mpg (8.62 L/100 km) Hwy: 42.3 mpg (5.56 L/100km)

Modeling the baseline vehicle for the EcoCAR proposal provided the energy use at the wheels of the vehicle over an urban dynamometer drive schedule (UDDS). The EcoCAR RFP specifies a 1 Hz UDDS cycle for analysis. To model the Malibu, HEVT used a force balance on the vehicle to determine the necessary tractive effort for each time step. The force balance is illustrated in Figure 3 [16]. F_I represents the inertial force, F_{Aero} is the force due to aerodynamic drag, F_{rr} is the force of rolling resistance, and F_{Tr} is the resulting tractive force at the wheels to propel the vehicle.

Figure 3. Force balance on 2008 Chevrolet Malibu.

Johnson et al describe the process used to determine drive cycle information during modeling as follows:

> To determine the total propulsion energy required to propel the vehicle over the drive cycle, the power required to propel (F_{Tr} >0) was summed over each time step. The average power required to propel the vehicle at the wheels, 4.12 kW, was then derived from averaging the total positive propelling power over the time of the whole drive cycle. The peak power output at the wheels was 37.3 kW. Table 7 summarizes the results from the baseline vehicle modeling exercise. It is important to note that the energy use reported is only valid for the baseline vehicle characteristics and energy use will change if the characteristics deviate from the original vehicle [16].

Table 7. 1 Hz UDDS drive cycle results

Metric	Response
Total Positive Propulsion Energy Required at the Wheels [kWh]	1.57
Average Positive Propulsion Power at the Wheels [kW]	4.12
Peak Power Output at the Wheels [kW]	37.3
Percent Idle Time [%]	17.8
Force	Energy at the Wheels [kJ]
Aerodynamic Drag	1300
Rolling Resistance	1570
Total Road Load	2870
Positive Inertia	3755
Negative Inertia	-3755
Total Net Inertia	0
Total Energy	**2870**

3.4 Fuel Selection

With the design targets set by the RFP, the baseline vehicle energy use modeled, and the vehicle architecture selected, the fuel selection process begins by evaluating the fuels available for the competition. The EcoCAR RFP outlines the available fuels as,

> those with renewable content that meet the California Low Carbon Fuel Standard: E10 (90% California Phase II reformulated gasoline and 10% denatured ethanol), E85 (85% denatured ethanol and 15% California Phase II reformulated gasoline), and B20 (80% ultra-low sulfur diesel and 20% biodiesel), along with the energy carrier hydrogen (in its gaseous form) and the energy carrier electricity [13].

To meet the HEVT defined goal of having a large reduction of petroleum use, a fuel or energy carrier must be chosen that contains little or no petroleum itself or in its manufacture. The competition will evaluate not only the energy content of the fuel, but also the energy required to produce the fuel. The tool used for this calculation is the ANL developed Greenhouse gas, Regulated Emissions, and Energy use in Transportation (GREET) model [17]. The model calculates the well-to-pump (WTP) or upstream energy use and emissions for a fuel or energy carrier. Using this information, E85, hydrogen, and grid electricity were identified as candidate fuels and energy carriers. All three of these energy sources or carriers will be examined in the SPHA design process. The APU to use E85 will be in an internal combustion engine (ICE) with a generator, gaseous hydrogen fuel will be used in a fuel cell, and grid electricity will be stored in a battery pack.

3.5 Matlab Model

After selecting a powertrain and fuel, it is necessary to create a model to simulate powertrain operation to determine powertrain efficiency and model all of the losses. The goals of the model are to determine how much energy input is required for a drive cycle, the power use of components at each step of the drive cycle, and the energy loss of each component for a drive cycle. To determine the energy use at the wheels, the model opens a drive cycle, and then calculates road and inertial load for given vehicle parameters. From the tractive effort, the mechanical output and electrical input powers of the traction drive system are calculated. A control strategy function is called which determines how much battery or fuel converter power is needed. The battery and fuel converter models are both called which determine the operating efficiency of their respective components. Finally, the fuel input power is calculated. At each step and for each component, a corresponding power loss is calculated. The model is written to calculate fuel energy input from the energy output at the wheels through a series of component efficiencies. The energy flows can be seen in Figure 4. Appendices B and C contain the model code.

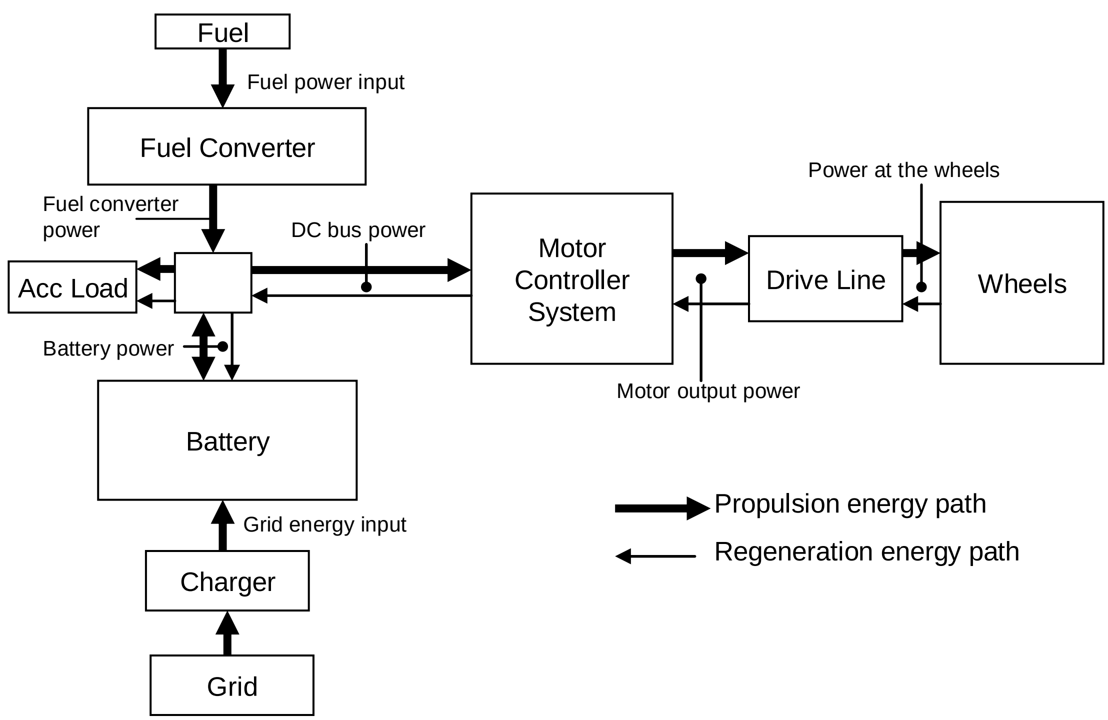

Figure 4. Energy flow diagram for SPHEV model.

3.5.1 Conventions

Battery power out is positive. Velocity for a time step is average of previous and current velocity.

3.5.2 Tractive Effort

The tractive effort is defined as the force at the wheels necessary to overcome friction and inertia over a drive cycle. As velocity changes, the tractive effort changes and the required output of the powertrain changes. The two components of frictional road load are rolling resistance and aerodynamic drag. Inertial load and grade load are conservable forces and can be recaptured.

Rolling resistance is associated with the deformation of the tires as they rotate. During rotation, a section of tire impacts the road, is loaded by the weight of the vehicle, and is then unloaded as a new section impacts the road while the vehicle continues to travel forward. The equation for rolling resistance is given by Equation 1:

$$F_{RR} = mgC_{rr} \tag{1}$$

where m is vehicle test mass, g is the acceleration of gravity, and C_{RR} is the coefficient of rolling resistance. This model is independent of velocity. Data for specific vehicle rolling resistance can include a velocity component. In this situation, the F_{RR} is reported as given in Equation 2:

$$F_{RR} = F_0 + F_1 \cdot v \tag{2}$$

where F_0 is the zeroeth-order coefficient, F_1 is the first-order coefficient, and v is velocity.

As a vehicle is propelled, it generates friction with the atmosphere it is traveling through. This friction is referred to as the aerodynamic drag. The drag force is given by Equation 3:

$$F_{AERO} = \frac{1}{2}\rho A_f C_D v^2 \tag{3}$$

where ρ is the density of air, A_f is the frontal area of the vehicle, C_D is the drag coefficient of the body, and v is the vehicle speed. For a given vehicle and atmospheric conditions, a single aerodynamic drag coefficient can be given to simplify calculation. In this situation, the equation for the drag force is given by Equation 4:

$$F_{AERO} = F_2 \cdot v^2 \tag{4}$$

where F_2 is the simplified coefficient.

The third component of tractive effort is the inertial force. The inertial force is the load due to the acceleration of the mass of vehicle and follows the form of Newton's 2nd law as shown in Equation 5:

$$F_{INERTIAL} = rma \tag{5}$$

where r is the rotational mass factor, m is the vehicle test mass, and a is the acceleration of the vehicle. The rotational mass factor is necessary to account for the rotating inertia of the drive line.

The fourth component of tractive effort is the force due to grade. The force due to grade is the component of gravitational force along a grade. Grade is typically expressed in percent grade. For simplicity, it is easier to use an angle for the grade as in Equation 6:

$$F_{GRADE} = mg \cdot \sin(\alpha) \quad , \tag{6}$$

where m is the vehicle mass, g is the acceleration due to gravity, and α is the angle of the road from horizontal.

The total tractive force is the sum of the force of rolling resistance, aerodynamic drag, and grade. This is expressed in Equation 7:

$$F_{Tr} = F_{RR} + F_{AERO} + F_{INERTIAL} + F_{GRADE} \quad . \tag{7}$$

Combining the separate equations to determine the tractive force at the wheels gives Equation 8:

$$F_{Tr} = F_0 + F_1 \cdot v + F_2 \cdot v^2 + rma + mg\sin(\alpha) \quad . \tag{8}$$

The tractive power at the wheels is the tractive force multiplied by the velocity. This is shown in Equation 9:

$$P_{Tr} = F_0 \cdot v + F_1 \cdot v^2 + F_2 \cdot v^3 + rma \cdot v + mg\sin(\alpha) \cdot v \quad . \tag{9}$$

The power at each time step in a drive cycle is recorded. By multiplying by the time step, the energy use at each time step is able to be calculated. The velocity used in calculations is the average velocity between the previous and current time step.

3.5.3 Motor-Controller efficiency

After calculating the tractive power, the power output of the electric traction drive must be calculated. Since the traction drive is an AC induction machine, there is a drive line loss between the motor rotor torque output and the torque at the wheels. A constant efficiency loss is assumed for the drive line. The drive line loss applies for both positive and negative torques, so a split equation must be used. When the torque is positive, the tractive torque is a divided by the drive line efficiency, thereby calculating the motor's required output torque. Conversely, when the torque is negative, the tractive torque is multiplied by the drive line efficiency, reducing the amount of torque available to the motor for regenerative energy capture. The motor is connected to the drive line through a direct, single speed gear reduction resulting in motor speed being directly tied to vehicle speed as dictated by the drive cycle. The motor-controller efficiency is then determined by the motor-controller function (MCF).

The MCF defines the motor-controller efficiency as the ratio of the electrical power input on the direct current (DC) bus to the mechanical power output to the driveline. The efficiency of a motor and controller, η_m, is modeled by Equation 10:

$$\eta_m = \frac{T\omega}{T\omega + k_c T^2 + k_i \omega + k_w \omega^3 + C} , \tag{10}$$

where T is the rotor torque, ω is the rotor rotational velocity, k_c is the copper loss, k_i is the iron losses, k_w is the friction and windage losses, and C is a constant loss [19]. The copper loss is due to the resistance of the wiring in the motor. The iron loss is due to the rotating magnetic field and rotor losses inside the motor. The friction and windage losses are caused by bearings and other sources of rotational losses such as fans. The constant loss applies to motors where there are losses even if the motor is not moving, such as a separately excited motor. The motor efficiency over the torque-speed plot is shown in Figure 5.

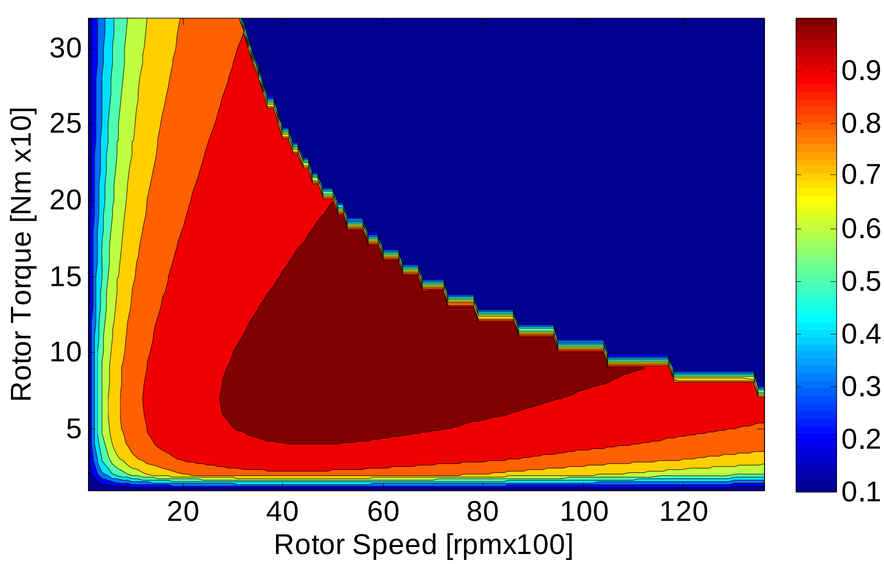

Figure 5. Motor efficiency plot.

To model calls the MCF at each time step. The model passes the required motor output power and the rotor speed to the function. After setting the constants, the MCF determines if the model is requesting more power than the motor can supply. The MCF then converts the rotor speed from revolutions per minute to radians per second. The torque required to produce the required motor output power is calculated. Using Equation 9, the MCF calculates the efficiency of the motor-controller. An efficiency floor of 20% is set in the MCF. This prevents engine start at near zero speeds when efficiency would be very low, such as when accelerating from a stop, by preventing the electrical power requirement of the motor-controller from becoming greater than engine start power during light accelerations. The motor-controller power demand is combined with the accessory load to create the DC bus power demand (as shown in Figure 3). The control strategy function then selects what source will meet the DC bus power demand.

3.5.4 Control Strategy

The control strategy function (CSF) selects powertrain mode and determines how much of the energy used by the motor-controller is delivered from the battery or the fuel converter for each time step. The CSF reads in seven variables: the required DC power that must be supplied to the motor-controller, the state at the end of the previous time step, the battery SOC at the end of the previous time step, a run bit which indicates whether or not the fuel converter has met the minimum runtime requirement, and the low limit, high limit and target battery SOCs. Figure 6 shows the battery SOC range with operational modes.

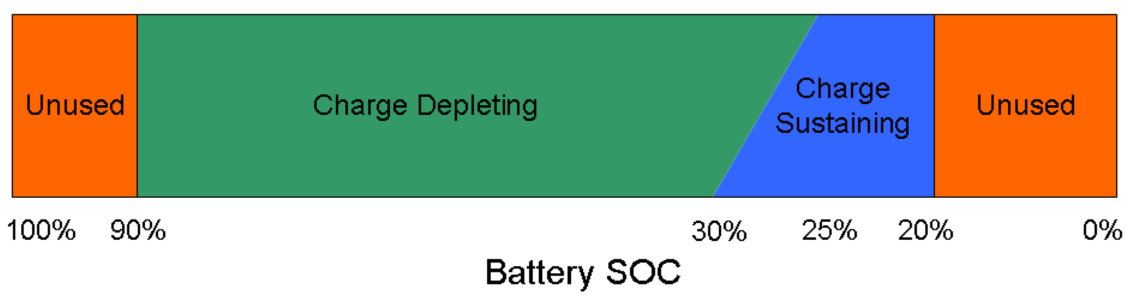

Figure 6. Battery SOC with overlaid operational modes.

The first process in powertrain operation selection is to determine if the fuel converter must run. The fuel converter must run if it had previously been used and the minimum run time requirement has not been met. The minimum run time allows the fuel converter and emission controls to reach operating temperature. Three states are available. State one is the all electric mode where engine starts are prohibited, state two is entered with the fuel converter off, but it may start if power levels or battery SOC require it, and state three is selected when the fuel converter must run.

SOC management is key to charge sustaining operation. If SOC drops too low, the vehicle will lose performance and the consumer will be dissatisfied. High battery losses and potential damage to the battery pack are also concerns at low SOC. To prevent performance robbing SOCs, state three is the first condition checked for in the CSF. State three is selected when the SOC is below the low limit. This forces the fuel converter to run, disregarding the required DC bus power. If the fuel converter is forced to run, when the DC bus power is lower than the minimum fuel converter output power, the excess is stored in the battery, raising the SOC. When SOC is five percent or more below the low limit, mode three is selected and the fuel converter set to run at peak power, providing maximum battery charging capability. Once the CSF determines that state three has been selected, the next check is whether the DC bus power is positive or negative. If the DC bus power is positive, the next check determines if the demand is greater than, less than, or within the output range of the fuel converter. When the demand is greater than the design output of the fuel converter, the fuel converter runs at peak load, and the battery must supply the additional power to meet the demand. If the fuel converter is able to meet the demand, the fuel converter alone operates. If the demand is less than the minimum power set point output of the fuel converter, then it operates at the minimum load and charges the battery with the excess power. If the demand is negative and the fuel converter must run, the fuel converter operates at the minimum power. The battery is charged with the fuel converter power and the negative power from the motor-controller. If this amount exceeds the recharge power limit of the battery, the friction brakes are engaged, turning the excess power into heat.

State one is the next check in the CSF. It is selected when SOC is above the high limit and the fuel converter is not required to run. For all electric range, the battery starts each test with a 90% SOC and is depleted to the target SOC, which is the midpoint between the low and high limits. Once the battery reaches the target SOC, it switches from a charge depleting mode to a charge sustaining mode. State one is no longer available, since the SOC has dropped below the high target. The fuel converter use is allowed and states two and three are selected. For this state, propulsion power is supplied by the fuel converter and battery, and all deceleration power is captured up to the recharge power limit of the battery, at which point the friction brakes are engaged, dissipating excess energy as heat.

If neither state one or three are selected, the default is state two. State two is similar to state one, but does not start with the assumption that the engine is already running. If the power demand on the DC bus is greater than the minimum power level set for fuel converter start, it operates the fuel converter at the output power level up to the maximum. If the demand is greater than the maximum fuel converter power, the battery meets the excess demand. If demand is lower than the fuel converter minimum start power, the battery alone meets the demand. For negative demand, the fuel converter remains off, and the battery recharges up to its recharge power limit when the friction brakes are engaged. If the fuel converter turns on, the run bit is set to “on” for all future time steps up to the minimum run time.

3.5.5 SOC Biasing

Depending on the drive cycle, it is possible for SOC to climb above the high limit for charge sustaining operation due to the minimum engine run time. It is undesirable to have the SOC rise above this limit as it decreases the amount of energy that could be absorbed by grid charging which displaces onboard fuel use. It is also undesirable for the

SOC to be too low as not enough energy is available to meet high driver demand for sustained periods of time. To help prevent SOC from reaching the high limit, SOC biasing is employed. SOC biasing favors battery or fuel converter power based on SOC. At low SOC, the fuel converter is employed at increased power levels to recharge the battery. Similarly, at higher SOCs, the energy from the battery is favored to decrease SOC. The SOC bias is a percentage of fuel converter demand that is shifted to the battery based on SOC. Figure 7 shows an example of the effects of SOC biasing on a 25 kW power demand from the fuel converter. At the target of 25% SOC, the fuel converter produces 25 kW and the battery provides zero. SOC biasing represents a limited method of control to manage SOC and it does not take into account fuel converter efficiency. Due to the differing nature of the two fuel converters chosen, SOC biasing does not represent a strategy optimized for either fuel converter, but allows direct comparison of energy paths.

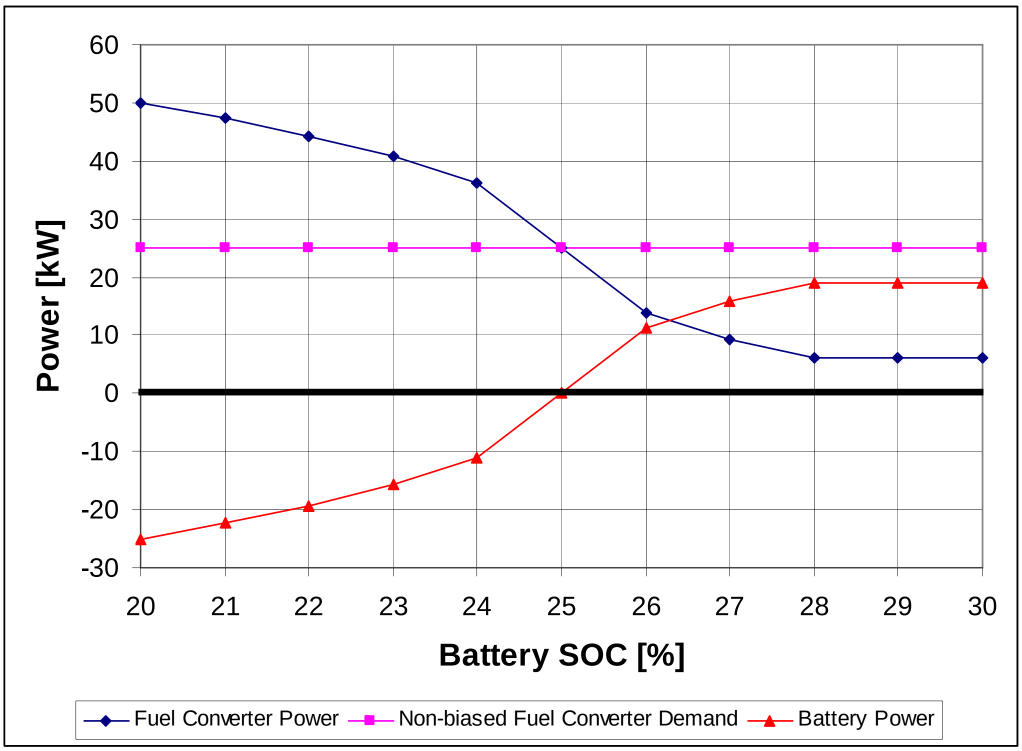

Figure 7. SOC biasing effects on fuel converter and battery power.

SOC bias is calculated after the battery and fuel converter powers have already been calculated in the previous section, and only occurs when the DC bus power demand is positive. Since the fuel converter is not capable of recapturing brake energy, it is more efficient to use the battery. The bias numeral, b, is calculated in Formula 11:

$$b = \frac{2(\text{SOC} - \text{Target})}{\text{SOC Range}} \quad (11)$$

The bias coefficient is calculated as the square root of b. When b is negative, the absolute value of b is taken before the square root and the result is multiplied by a negative one as illustrated in the following code fragment:

```
if b1 > 0
   bias = sqrt(b1);
else
   bias = -sqrt(abs(b1));
end
```

A positive bias coefficient favors battery power while a negative bias coefficient favors fuel converter power. The cases of fuel converter required to run and fuel converter not required to run require separate battery and fuel converter power output calculations. The case of fuel converter must run is examined first. When the bias is positive, the first check is to determine whether biasing towards battery power will run the fuel converter below the minimum power level of the fuel converter. If this is not the case, then the battery power is increased using the bias coefficient as the percent of original fuel converter power that the battery power is increased by and the fuel converter power is decreased by. If the fuel converter would have been biased below the minimum power, the fuel converter runs at minimum power and the battery is increased only to make the difference. If the fuel converter does not have to run, a bias coefficient that would run the fuel converter below the minimum power level simply uses the battery only and does not run the fuel converter.

When bias is negative, the fuel converter will run with a higher power output than is required by the DC bus demand. In this case, there is no distinction between engine required to run and not required to run. It is necessary to prevent the fuel converter from operating above the maximum power output level. The section prior to SOC biasing will prevent the fuel converter from operating below the minimum power level since negative bias only adds to the fuel converter output level. A flowchart representing bias decisions is shown in Figure 8. The result is a combination of fuel converter and battery output powers that prefer the SOC at the target level. The further from the target SOC, the higher the bias, which yields a charge sustaining control strategy. Figure 9ab illustrates the effect of biasing control on SOC. Both plots are of the same vehicle on the same drive cycle. The SOC range is from 20% to 30% and a target value of 25%. The example with biasing shows the control strategy maintaining the SOC near the target value while the example without biasing shows the SOC leaving the target range.

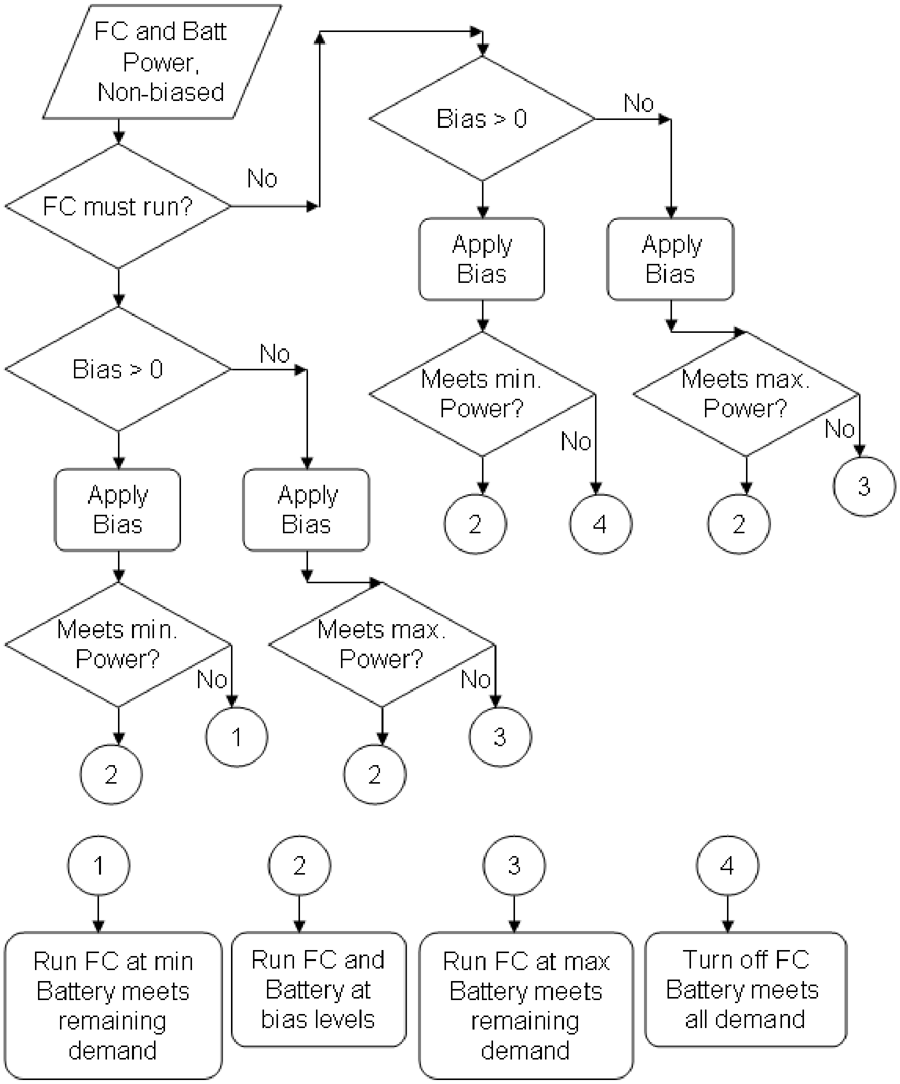

Figure 8. SOC Bias flowchart.

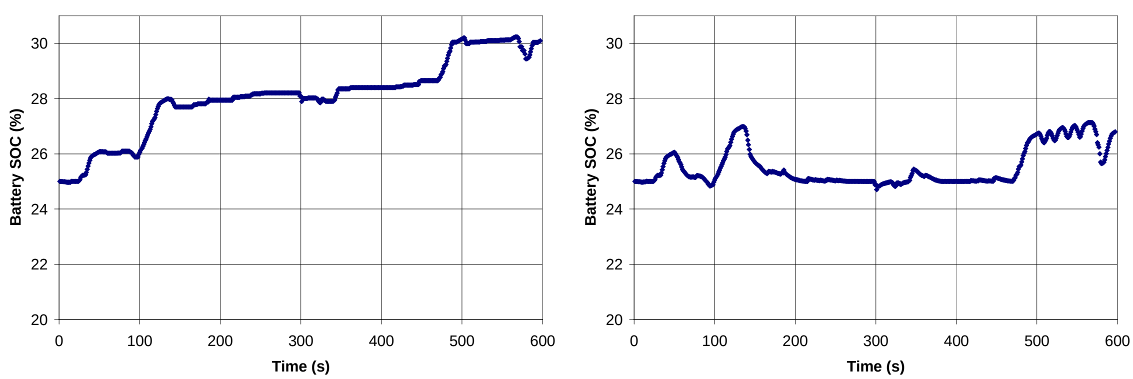

Figure 9ab. The effects of SOC biasing can be seen. The plot on the left is without biasing and the plot on the right is with biasing.

3.5.5 Battery efficiency

The battery model was first developed by Boyd et al. at Virginia Tech [11]. Compared to other models, such as ANL's PSAT [25], the level of complexity is less in the Boyd model. With fewer inputs, the Boyd model provides a simple tool that is reasonably accurate for losses for part load drive cycles [11]. The model tracks the stored energy in the battery, represented as SOC, the internal losses of the battery, and the battery voltage.

The battery model function (BMF) is called after the CSF has determined how much power the battery must supply to meet the DC bus demand. The inputs to the BMF are the battery required power, previous SOC, the nominal battery voltage, the fully charged voltage, the energy capacity of the battery, and the model time step.

To calculate the internal power of the battery, which includes the terminal power and the internal losses, the required terminal power is passed to the BMF. The BMF then calculates internal power using one of two resistances. The charge resistance is used when the terminal power is negative, resulting in an increase of stored energy and the discharge resistance when the terminal power is positive, requiring energy from the battery. The open circuit voltage, *OCV*, is calculated using Equation 12:

$$OCV = Nom + SOC \cdot \left(OCV_{full} - Nom\right) \tag{12}$$

where *Nom* is the nominal battery voltage and OCV_{full} is the battery voltage at 100% SOC. Battery current, *I*, is then calculated as shown in Equation 13:

$$I = \frac{OCV - \sqrt{OCV^2 - 4RP}}{2R} \tag{13}$$

where *R* is the appropriate resistance and *P* is the battery terminal power. The resistance is determined by the sign of the terminal power. If the power is positive, the discharge resistance is used. Conversely, if the power is negative, the charge resistance is used. The losses due to internal resistance of the battery, P_{loss}, is calculated in Equation 14:

$$P_{loss} = I^2 * R \quad \cdot \tag{14}$$

The power losses due to internal resistance are added to the battery terminal power, P_{term}, to find the total internal power of the battery, as in Equation 15:

$$P_{total} = P_{term} + P_{loss} \quad . \tag{15}$$

Since the power losses will always be positive, they serve to increase power demand when terminal power is positive and decrease power demand when terminal power is negative. This represents an increase of internal power when using battery power, and a decrease in the power being stored when charging the battery. Figure 10 illustrates the effect of battery power loss on propulsion power. Figure 11 shows the reduction in stored power during regenerative braking due to internal battery resistance.

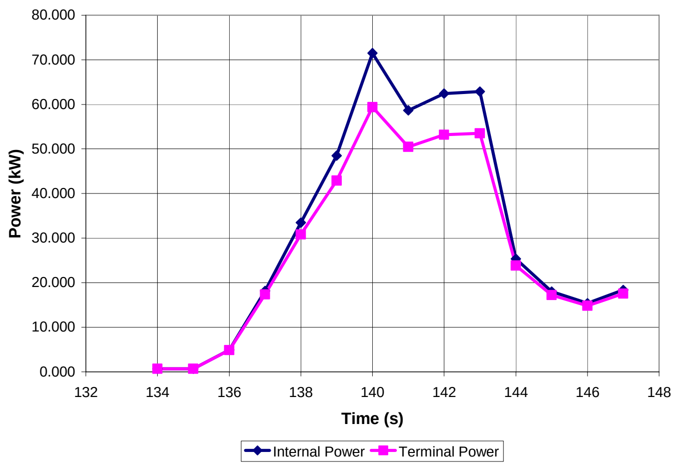

Figure 10. Propelling power requirement is shown to be increased due to internal battery losses.

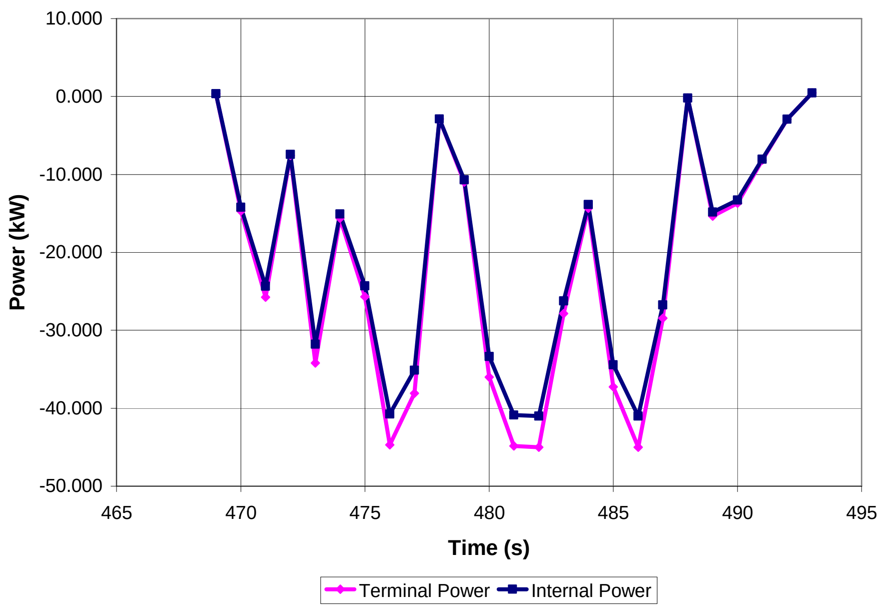

Figure 11. Battery terminal and internal powers for regenerative brake energy capture.

3.5.6 Fuel Converter efficiency

The fuel converter efficiency is two separate functions. Either the fuel cell or the engine-generator function is used. When one is not in use, the function is merely commented out of the code. The engine-generator code set contains more outputs, which allow for a more detailed look at the engine running conditions if desired.

The first function approximates the efficiency of a fuel cell system as a function of percent load. Percent load is calculated as the fuel converter power calculated by the control strategy divided by the maximum output power available from the fuel converter. The efficiency function is a lookup table with input values of 0, 15, 35, and 100 percent load. The output represents the fuel cell system efficiency (fuel energy input to net DC power output). The outputs of the lookup table are 0, 0.55, 0.5, and 0.4 efficiency. Figure 12 shows the fuel cell efficiency curve. Before the function returns the efficiency, it is multiplied by a constant efficiency of 0.96. This represents the loss associated with a boost converter, which would be necessary to combine stack and battery power as stack voltage sags under load.

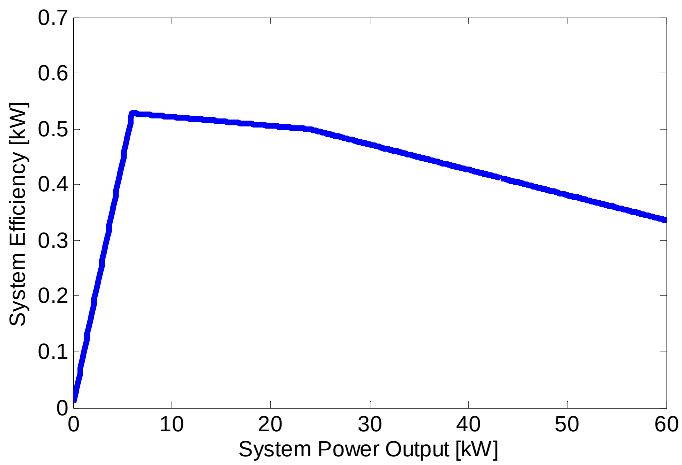

Figure 12. Fuel cell system efficiency plotted against system power output.

The second variation of the fuel converter efficiency function is the engine-generator function (EGF). The EGF approximates the operation of a simple engine coupled with a constant efficiency generator to produce DC power from fuel.

The EGF first calculates the required engine power output level by dividing the required output power by a constant generator efficiency of 92%. The engine is then operated along a single line in a torque-speed plot. This can be seen in Figure 13. The base speed is the minimum speed at which the engine will operate when commanded by the control strategy. The base speed is set to the approximate lug limit of an internal combustion engine at 1300 rpm. Below this, engines run poorly and may hesitate. The peak torque at the minimum speed is referred to as the base peak torque. The EGF checks the engine required power output level against the power the engine is able to produce at the peak torque available at the base speed. If the demand is lower than this power limit, the engine operates at the base speed and the necessary torque level to meet the demand. If the demand is higher than the power available at the base speed and peak torque, the engine speed and torque are incrementally increased until the engine meets the power demand. The rate at which the torque increases with respect to the engine speed is called the torque rising rate. The torque rising rate is the torque increase per rpm. This continues until a peak torque is reached, which is lower than the peak torque the engine is capable of creating to keep efficiency high, at which point only the engine speed increases to have power increase.

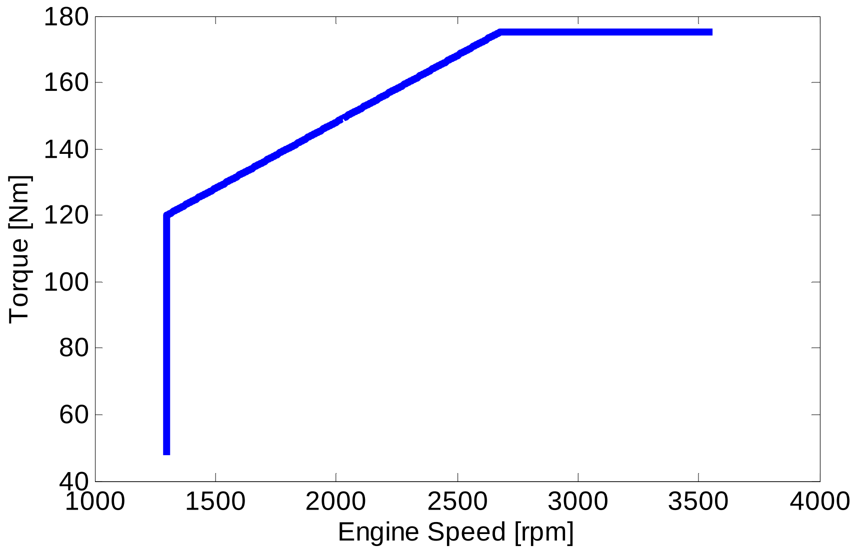

Figure 13. Torque-speed operation curve for 1.4L engine operation from 6 to 60 kW.

The EGF then calculates the efficiency of the engine, η, using Equation 16:

$$\eta = \frac{\eta_{thermo}}{\left(1 + \frac{FMEP \cdot Displacement}{4 \cdot \pi \cdot Torque}\right)} \tag{16}$$

where η_{thermo} is the indicated thermodynamic efficiency, *FMEP* is the friction mean effective pressure, *Displacement* is the engine displacement in liters, and *Torque* is the calculated torque output level. Equation 16 is simplified from research done by Nam and Sorab [20]. Figure 14 displays engine efficiency as it varies with power.

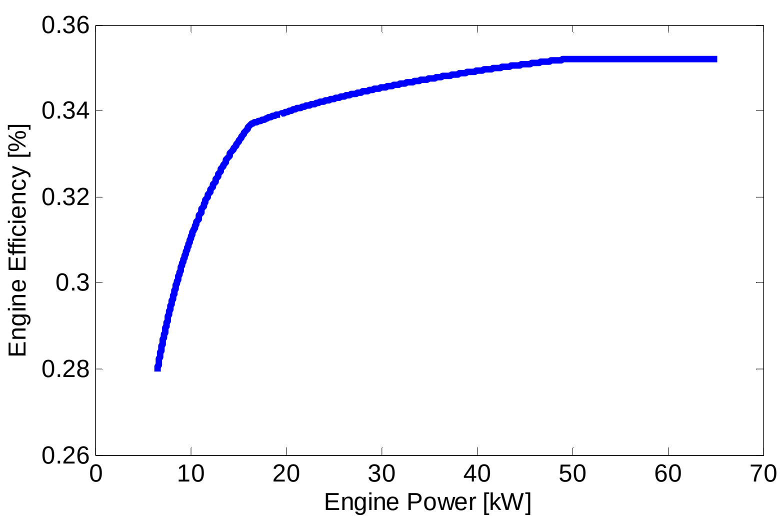

Figure 14. Engine efficiency is plotted against engine power output.

This engine model is simplified. It does not take into consideration the increased friction and therefore decreased efficiency of higher speed operation. This simplification is acceptable in the speed ranges the engine is most likely to operate in, high torque and low speed, which provides the best efficiency. The model also neglects enrichment for component and catalyst protection at near peak loads. This is acceptable due to the use of E85 as a fuel, which burns cooler than gasoline, and therefore doesn't require over fueling.

3.5.7 Mode Switching

Once the CSF has determined whether or not the fuel converter must run, the model determines whether or not to switch the mode from charge depleting operation to a charge sustaining operation. The mode is switched if the SOC is below the target SOC. The mode is stored in a variable, and the next iteration of the calculation loop reads the mode with which it must operate. The mode switching functionality contains a check for high SOC in the event that the drive cycle produces many engine starts after charge depleting operation. If, during charge sustaining operation, the SOC is ever greater than the high SOC limit, the control strategy will operate in the original mode, shutting off the fuel converter.

3.6 Component Sizing

Now that a model has been produced, it is necessary to populate the model with components sized correctly for the vehicle to meet the CDTS. Specifications exist for fuel consumption, greenhouse gas emissions, range, acceleration, and top speed. Other specifications exist, but are not part of the performance model. Certain components needs to be sized for energy use, while others must be sized to meet performance requirements. For modeling, a 195 kg (430 lb) weight penalty is added for additional component mass compared to the stock vehicle. This brings the test mass of the vehicle to 1900 kg (4190 lb) compared to the stock test mass of 1705 kg (3760 lb). The energy use of the vehicle will, therefore, increase due to the higher inertial loads during acceleration and higher tire rolling resistance. Other vehicle characteristics remain the same as the stock vehicle.

3.6.1 Motor Sizing

Since the SPHA is a series architecture, the electric drive motor must be sized to provide full acceleration performance. This requires a high power drive system. To properly size the motor, a simple model is necessary to simulate a best effort acceleration event. The model used was developed for and used in ME 4554 Advanced Technology Vehicles. The model incorporates vehicle characteristics as well as motor characteristics. First the motor is modeled as an ideal motor torque-speed curve with constant torque up to the base speed and above the base speed, a constant power, with torque decreasing as speed increases up to the maximum motor speed. Figure 15 displays a motor model. This provides a maximum torque for a given speed. The vehicle characteristics are then used to determine how much time is necessary to accelerate the vehicle for each mph up to the desired speed based on the acceleration available from the motor. To meet the HEVT specified CDTS of 10 s from 0-100 kph (0-62 mph) using the provided vehicle specifications in Table UIO with a test mass of 1900 kg, a motor with a peak torque of 313 Nm up to a base speed of 3000 rpm and a peak power of 98 kW is necessary. Figure 16 shows the speed of the vehicle with respect to time. The motor base and maximum speeds were selected based on currently available traction drives used in some concept fuel cell and series plug-in hybrid vehicles. Thus the peak torque value was adjusted to meet the acceleration requirement, and that peak torque at the selected base speed determines the motor peak power. The single speed gearing between the motor and wheels combined with the selected maximum speed determines the vehicle top speed for the case where the motor has enough power to propel the vehicle at that speed.

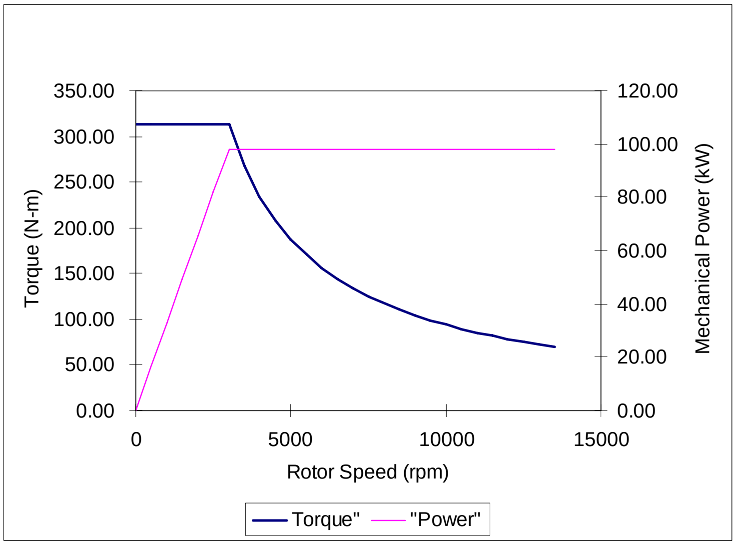

Figure 15. Motor model for motor sizing. Shown is a 98 kW motor with a peak torque of 313 Nm up to a base speed of 3000 rpm and a maximum speed of 13,500 rpm.

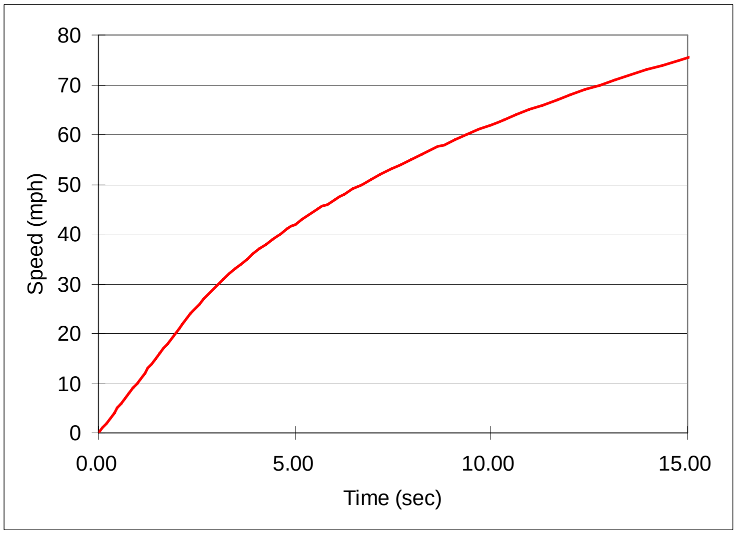

Figure 16. Vehicle speed with respect to time used for motor sizing.

3.6.2 Battery Sizing

The high voltage battery system on the vehicle stores energy electrochemically. The conversion of the chemical energy to electrical energy or vice versa involves losses. The power of the battery is measured at the electrical terminals of the battery. For sizing the battery, the internal stored energy of the battery is what will be referred to. The internal resistance of the battery produces losses between the terminals and the internal stored energy. The battery must be sized to meet the all electric range requirement.

The process used to size the battery starts with the model set up to run in CD mode. The battery SOC is set to 90% and the capacity is set to a nominal value, in this case, 10 kWh. A UDDS drive cycle, approximating city driving, is run, and from that, the amount of battery energy used is extracted. The battery energy divided by the number of kilometers driven is the average energy use per kilometer (kJ/km) for city driving. The same is repeated for the HWFET drive cycle and another average energy use per kilometer is extracted. The percentage of driving done in the city versus on the highway is used to determine a total energy use per kilometer. Knowing that the goal is a 65 km range, the total amount of energy storage that is needed in CD mode is the total energy use per kilometer is multiplied by the desired range. The energy available to propel the vehicle is not 100% of the battery capacity. To allow for charge sustaining operation and for extended battery life, the battery is never charged to higher than 90% SOC and is never discharged in CD mode below 25% SOC. At 25% SOC, the control strategy switches to CS operation. Table 8 summarizes the results from the battery sizing exercise. The table shows internal battery energy. The battery is capable of propelling the vehicle 65 km on a 65% SOC change (from an initial SOC of 90% down to 25%). The total energy used during that distance with a 55% city and 45% highway mix is 37700 kJ (10.5 kW-hr). This requires a battery of 16.1 kW-hr total internal capacity (100% SOC to 0% SOC) to meet the 65 km all electric range CDTS. The internal energy is the stored energy in the battery pack. Terminal energy refers to the energy at the battery terminals after battery losses have been accounted for. Terminal energy is lower than internal energy when energy is leaving the battery and the opposite when the battery is charging. The USABC minimum goal for long term commercialization for battery energy density is 150 Wh/kg [19]. Using this goal, a battery system with the capacity needed for this vehicle should weigh approximately 105 kg. This additional mass in the vehicle is accounted for as part of the 195 kg penalty discussed earlier.

Table 8. Battery sizing results. Energy use is battery stored energy.

Battery Sizing	
65	km Target Distance
55%	City Driving
45%	Highway Driving
UDDS	
12.0	km Driven
6543.4	kJ Battery Energy Used
71.8	% SOC End (CD only operation)
545.7	kJ/km
HWFET	
16.5	km Driven
10261.1	kJ Battery Energy Used
61.5	% SOC End (CD only operation)
621.6	kJ/km
Battery Sizing	
37691.5	kJ Required to travel AER distance
10.5	kW-hr Required
65.0	% SOC Available for CD
16.1	kW-hr Total Pack for Lithium-ion (Li-ion)
USCAR Battery Goals	
150	Wh/kg Energy Density Goal (Li-ion)
105	kg Battery Mass

3.6.3 Fuel Converter Sizing

The onboard fuel converter, either in the form of a fuel cell system or an engine and generator, must be sized so that the electrical output of the APU is sufficient to meet steady state load requirements. The steady state load used for sizing the fuel converter is a 6% grade at the vehicle's gross vehicle weight rating (GVWR) at a speed of 100 kph. With the APU operating and without using battery energy, the vehicle is capable of maintaining the target speed as long as it has fuel to do so. Higher speeds, which would realize higher loading on the vehicle, require more energy. It is possible for the vehicle to achieve higher speeds, but not without using battery energy. There are also situations where the vehicle may climb steeper grades, but most interstate driving, where aerodynamic loads are significant due to high speeds, will be limited to a 6% grade or less. A 60 kW electrical output from the APU is sufficient to maintain 100 kph on a 6% at GVWR. Table 9 summarizes the gradeability results for the vehicle. This power level is also sufficient to power the vehicle continuously at the design top speed of 90 mph (145 kph).

Table 9. Fuel converter sizing results.

Vehicle Gradeability	
Grade	6%
Vehicle Mass	2141 kg
Tractive Effort	50.5 kW
Speed	100 kph
APU Power Output	60 kW

For the case of the APU being a fuel cell system using the energy carrier hydrogen, the fuel cell system, including boost converter, must be rated to produce 60 kW of electrical power after meeting its own parasitic power needs. Figure 17 shows the fuel cell system efficiency curve used to model the fuel cell system. For the case of the APU being an engine and generator fueled by E85, the generator efficiency will require more power from the engine than is needed electrically. The model uses a constant efficiency of 92% for the generator. With an electrical output of 60 kW, the engine must be capable of producing 66 kW. Approximating current engine technology allows for the use of a 1.4L engine with a friction mean effective pressure of 170 kPa and an indicated thermodynamic efficiency of 39% to achieve 66 kW. The engine is loosely sized from a GM 1.4L engine. The engine is capable of producing power in the 88-104 kW range and torque between 175-200 Nm using advanced technologies like turbocharging and variable valve timing [21]. For the model, the lower torque value was used as peak torque. The engine is oversized for the APU, however, it must be noted that a constant 92% efficient generator does not exist, so the engine must be capable of meeting power demand at the lower efficiencies that would be experienced outside of the modeling environment. Figure RTY and RTY from section *previous* display the operation curve and engine efficiency versus the power output. Figure 14 displays the model engine efficiency with respect to torque output.

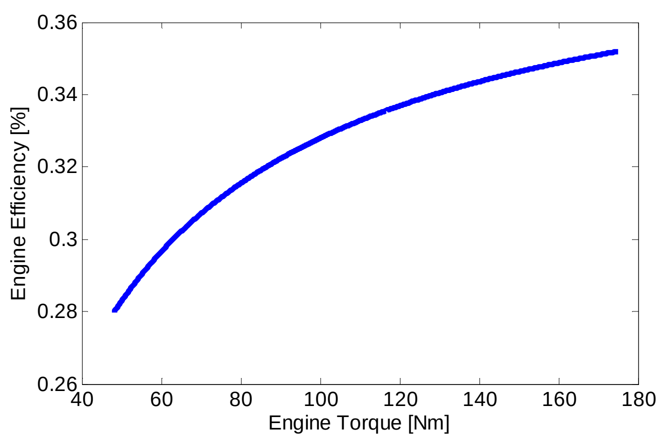

Figure 17. Model engine efficiency as it varies with the engine torque (load).

3.7 SPHA Design Considerations

The series plug-in hybrid architecture is shown in Figure 2. The architecture is similar to the GM's E-Flex architecture [22]. The E-Flex platform is the powertrain that is being developed for the 2010 release of the Chevrolet Volt. The Volt is slated to have a 120 kW electric traction drive, 53 kW range extending internal combustion engine, flex-fuel technology which allows the use of both gasoline and E85, and 16 kW-hr battery pack to provide a 40 mile all electric range [22]. The use of a full performance traction drive and appropriately sized battery allows the battery to propel the vehicle alone until the SOC reaches a level necessary for using the APU. This is in contrast to a low power battery which would not be able to provide power for full performance and would require an APU start to supply the traction drive with enough power to meet a high demand. Battery energy capacity and power capability are important factors to consider when selecting a battery pack for use in plug-in vehicles. Appendix A is a table with all model parameters used for the SPHEV.

4. Relationship Between Control Model and Vehicle

In developing a control model and strategy for the SPHEV, it is necessary to understand the energy paths, losses, operational modes, and energy sources so the results are easily compared to each other.

4.1 Energy Paths and Hybrid Modes

The SPHEV operates in one of two modes: charge sustaining or charge depleting. During the operation of a conventional vehicle, fuel energy is converted to rotational energy in the engine, which is transferred through the drivetrain to wheels providing propulsion. Similarly, the SPHEV's traction drive converts electrical energy into rotational energy and transmits it through a drivetrain to the wheels. Unlike a standard hybrid vehicle, the source of the energy has multiple paths. The paths are defined by the operational mode. In additional to having multiple energy paths, the SPHA can convert rotational energy at the wheels back into electrical energy through the traction drive and store it in the battery. This process is known as regenerative braking.

4.1.1 Charge Depleting Mode

Charge depleting mode uses energy stored in the battery to propel the vehicle. The stored energy in the battery decreases over time, and a fuel converter is not used to maintain SOC, so the mode is called charge depleting. The energy in the battery is able to be converted to rotational energy through the traction drive. Replenishing the energy used on the vehicle is accomplished by charging the battery from a wall outlet. The energy source for CD mode is the electric grid and the use of multiple primary energy sources that make up the national electric grid. The primary energy sources and their impact will be discussed later. The energy path is from the power plant, through transmission lines, transformers, and finally a battery charger which processes the incoming power and controls the battery charging.

4.1.2 Charge Sustaining Mode

Charge sustaining mode uses energy stored onboard the vehicle in a fuel in combination with battery energy to propel the vehicle. The amount of stored energy in the battery is maintained within desired limits by the fuel converter and the control strategy, so the mode is called charged sustaining. Due to the size of the fuel converter, the battery will act only as an energy buffer, used to load level the fuel converter and provide additional power when necessary. The two fuels being compared in CS mode are E85, an 85% ethanol and 15% reformulated gasoline blend, and gaseous hydrogen (GH2). The primary feedstock for current ethanol production is corn in the United States [17]. The corn is milled, cooked, fermented, and distilled to produce ethanol. In the GREET model, the default for gaseous hydrogen production uses natural gas as a feedstock and is generated at the refueling stations using steam methane reformation. Gaseous hydrogen is thus not a fuel, but rather an energy carrier. Since it will be used in a fuel converter, for purposes here, it will be referred to as a fuel. Neither of these paths represents the best case for efficient or renewable fuel production, but do represent a reasonable estimate of efficiency for current methods. Future E85 or GH2 production methods could be more or less energy efficient and have lower greenhouse gas emission if they are based on renewable energy sources. Replenishing used energy on the vehicle is accomplished by refueling with liquid E85 through a fill port like one on a conventional vehicle or in the case of gaseous hydrogen, a high pressure fill port as is used by demonstration hydrogen fueling stations now.

4.2 Meeting Driver Demand

With the controls modes mentioned above available, the vehicle must select when it is appropriate to use each based on driver demand the battery and stored energy level or SOC.

4.2.1 Negative Torque Request

To meet a negative torque request (braking), the control system has two options. As in a conventional vehicle, friction brakes can be used to decelerate the vehicle. More advantageous is the use of a regenerative braking, where the traction drive applies a negative torque through the driveline to the wheels. This generates a current in the opposite direction required for propulsion which can be used to charge the battery pack. The upper limit of the amount of power that is capable of being captured through regenerative braking is determined by the battery system. The model's upper battery power limit is 45 kW. In CD mode, 45 kW allows the powertrain to capture all of the braking energy on the UDDS and HWFET drive cycles. Up to 45 kW of braking power, the vehicle does not use the friction brakes, and uses the traction motor. Above that amount, and the friction brakes are added in addition to the traction motor. Regenerative braking is also limited by SOC. At higher SOCs, overcharging the battery becomes a concern as the voltage approaches upper limits for both the battery and components.

4.2.1 Positive Torque Request

To meet a positive torque request (propelling the vehicle, which can happen during mild decelerations), the control system must produce torque with the traction motor. The power to produce the torque can come from one of two electrical sources: the battery pack or the APU. The level at which the APU operates is determined by the CSF. The traction drive in conjunction with the CSF biasing must request electrical output from the APU greater than the minimum power requirement for the APU to start producing power. Once the APU is on, it must run at or above the minimum power requirement for the minimum run time. The minimum run time is set to 60 s (see below). The minimum power requirement without biasing is 6 kW to keep efficiency high (see Figure 11). The CSF biasing will request more power from the APU when SOC is below the target SOC, and reduce the request when SOC is above the target, but not below the minimum. If the minimum power requirement is not met due to biasing and the APU is not required to run, the APU will turn off. The battery pack will either supply or absorb power passively based on the power supply and demand of the other components on the high voltage bus.

The traction drive is modeled as a 3-phase AC induction motor with a single speed gear reduction. The maximum power the APU can provide to the high voltage bus is limited to 60 kW.

4.3 Initial Conditions and Assumptions

Some initial conditions and assumptions for modeling the SPHEV must be defined. The model has limited capability for emissions modeling. The minimum run time for the APU is an attempt to recreate some of the control necessary for emission control, but without a significantly more sophisticated engine model with emissions maps, it is not feasible to model emissions beyond complete combustion products. The minimum run time is meant to address the need to heat a three-way catalyst before it can effectively mitigate criteria emissions. Another assumption used in the model is that the traction motor is capable of supplying the necessary power to meet the drive trace and the battery and APU are capable of supplying the power to the motor. The model, including control system, also assumes that the components are not in a fault or failure mode. They would be operating within normal speed, temperature, current, voltage and torque limits. Since the model is most useful for component sizing, reviewing the peak operating points for each component will give the user an idea of what specifications are required.

4.4 GREET Model and Energy Sources

The GREET model produced by ANL is a useful tool for assessing the WTP or upstream energy use and emissions of a particular fuel or energy carrier. This takes into account the raw material, processing or generation, and distribution of each fuel. Using this fuel model, a vehicle model is normalized to the fuel it uses. An inefficient vehicle using a fuel with low WTP energy use could conceivably use less energy per mile than an efficient vehicle with a high WTP energy use. The three fuels or energy carriers to be examined are E85, gaseous hydrogen, and electricity from the US national grid as they provide the lowest petroleum content of the EcoCAR competition fuels.

As defined by the EcoCAR RFP, E85 is a mixture of 15% California Phase II reformulated gasoline and 85% denature alcohol by volume. The GREET model lists the energy content of California reformulated gasoline as 113,927 Btu/gal (31,753.3 kJ/L) and 76.330 Btu/gal (21,274.4 kJ/L) for ethanol. Blended together at the proper ratio for E85 gives 81970 Btu/gal (22,846 kJ/L) or 72% of the energy per volume of reformulated gasoline. The gasoline production uses a refinery efficiency of 85.5% and additional transportation losses on the order of 6%. In the GREET model, ethanol production can be simulated using a corn feedstock or a cellulosic feedstock. Since corn is currently the predominant method of producing ethanol in the United States, the default for 100% corn feedstock is used. Corn ethanol is produced at a rate of 2.72 gallons per bushel and uses 36,000 Btu/gallon of fossil fuel energy and electricity for fuel production. The break down of fossil fuels used to produce the ethanol is 80% natural gas and 20% coal. Ethanol from corn uses 1.27 MMBtu per MMBtu of energy in the fuel. This can be compared to the GREET model's estimate of cellulosic ethanol production from corn stover which uses 0.899 MMBtu per MMBtu of energy in the fuel. Clearly, traditional corn based ethanol production has a limited future as less energy intensive options become available.

Like ethanol, gaseous hydrogen must be produced before it can be used as a fuel. Hydrogen is capable of being produced from a variety of feedstocks including natural gas, coal, and water. The processes used to generate the hydrogen are steam-methane reformation (SMR), coal gasification, and electrolysis. Electrolysis and SMR can be done on a small scale such as at the refueling station or a consumer's home. The WTP energy associated with hydrogen are also modeled by the GREET model. Gaseous hydrogen contains 113730 Btu/kg. The model for current hydrogen production uses natural gas as the feedstock at the refueling station, creating a release of CO2 during the production of the fuel. Since the process takes place at a smaller scale, the efficiency is lower than if the process were taking place at a centralized plant. The production of hydrogen uses 742 kJ of energy per MJ of fuel energy, of which 712 kJ is fossil fuel.

Grid electricity is produced in a variety of methods across the country. Many different fuels supply energy for electrical power generation. For each MJ of energy carried to the vehicle, 1.64 MJ of energy is used, of which 1.58 MJ is from fossil fuel. For the United States, Table 10 summarizes the generation mix. A majority of plants in the US are coal fired due to the large quantity of global reserves that are in the US. Since the burning of coal, natural gas, and oil for power generation releases CO2 into the atmosphere, grid electricity has a greenhouse gas emission of 741 g/kW-hr associated with its use at the wall outlet. Table 11 shows the WTP energy use for all three fuels.

Table 10. Generation mix for the United States [17].

Type	Generation Mix
Residual Oil-Fired Power Plants	2.7%
Natural Gas-Fired Power Plants	18.9%
Coal-Fired Power Plants	50.7%
Biomass Power Plants	1.3%
Nuclear Power Plants	18.7%
Other Power Plants (hydro, wind, geothermal, etc.)	7.7%

Table 11. WTP energy ratios and consumption [17].

Well-to-Pump Energy Ratios (J Energy Used/MJ downstream fuel)				
	RFG	E85	GH2	Electricity
Total Energy Input	254,163	1,274,531	741,894	1,635,139
WTP Efficiency	79.7%	44.0%	57.4%	37.9%
Fossil Fuels	219,140	630,101	712,631	1,578,568
Petroleum	91,345	88,536	15,914	88,445
% of Petroleum in Vehicle Fuel	90%	19%	0%	0%

The organizers of the AVTCs have adapted the complex GREET model into a set of easy to use equations and tables for the purpose of reducing confusion. The first table, Table

12, associates the WTP GHG release in grams to the fuel energy used in millions of Joules. The total GHG factor is determined by Equation 17,

$$GHG = CO_2 + 21 \cdot CH_4 + 310 \cdot N_2O \tag{17}$$

The total upstream GHG emissions can then be calculated as simply a function of type and amount fuel used as shown in Equation 18,

$$Total_{WTP} = GHG\left[\frac{g}{MJ}\right] \cdot Fuel\ [L] \cdot Energy_{Fuel}\left[\frac{MJ}{L}\right] \quad , \tag{18}$$

where *Fuel* is the amount of fuel used and *Energy* is the energy density of the fuel. The total amount of GHG release is determined by the upstream WTP component and the combustion of the fuel in the vehicle known as pump-to-wheels (PTW). The PTW GHG calculations is shown in Equation 19 and is expressed in terms of grams per kilometer,

$$Total_{PTW} = \frac{C_{ratio-fuel} \cdot \rho_{fuel} \cdot Fuel_{used}}{C_{ratio-CO2}} \quad , \tag{19}$$

where $C_{ratio\text{-}fuel}$ is the carbon ratio in the fuel, ρ_{fuel} is the density of the fuel, $Fuel_{used}$ is the amount of fuel used, and $C_{ratio\text{-}CO2}$ is the carbon ratio of CO2. Combining Equations 17 and 18 gives Table 13 for each fuel. Since grid electricity and gaseous hydrogen do not contain carbon in the energy carriers, there are no PTW GHG emissions. Note that even though grid electricity and gaseous hydrogen do not have any PTW GHG emissions, they are significantly higher in WTP and WTW GHG emissions than E85 based on current production methods. This is due to E85's absorption of CO2 during feedstock growth which is subsequently released during combustion.

Table 12. WTP GHG emissions condensed from GREET in grams/MJ [23].

	RFG	**E85**	**GH2**	**Electricity**
CO2	18.53	-14.47	91.93	179.4
CH4	0.11	0.10	0.14	0.25
N2O	0.00	0.03	0	0
Total GHGs	21.35	-3.68	94.92	185.8

Table 13. PTW and WTW GHG emissions per fuel energy content.

Fuel	**Upstream GHG**	**CO2 Content of Fuel**	**Total GHG**
	[g CO2 equiv/MJ]	[g CO2/MJ]	[g CO2/MJ_{FUEL}]
RFG	21.35	72.7	94.05
E85	-3.70	71.3	67.6
GH2	94.9	0.0	94.9
Electricity	185.8	0.0	185.8

In addition to WTP and PTW GHG emissions, the AVTC organizers have adapted the GREET model into an equation and table, greatly simplifying calculations. Table 14 is derived from the competition petroleum energy factor for each fuel or energy carrier. The total energy is the total energy for manufacturing the fuel (WTP energy). Petroleum energy is the amount of the total energy that is derived from petroleum. It is notable that reformulated gasoline (RFG) is greater than one.

Table 14. Petroleum energy use for competition fuels.

	Fuel Energy	WTP Petroleum	Upstream Petroleum	Petroleum in Fuel	Downstream Petroleum	WTW Petroleum Energy Use
Fuel	MJ	J/MJ_{FUEL}	MJ/MJ_{FUEL}	%	MJ/MF_{FUEL}	MJ/MJ_{FUEL}
RFG	1.00	91,345	0.0913	90%	.090	0.9913
E85	1.00	88,536	0.0885	19%	0.19	0.2785
GH2	1.00	15,914	0.0159	0%	0	0.0159
Electricity	1.00	88,445	0.0884	0%	0	0.0884

Examining the total petroleum energy use of the competition fuels shows that the three selected for comparison here are low petroleum fuels. They were selected to help achieve a large impact on petroleum energy consumption. Grid electricity and gaseous hydrogen each have less than 5% petroleum energy content. Due to the very low petroleum content, using gaseous hydrogen will require less powertrain efficiency to achieve the same decrease in petroleum consumption compared to E85. If, however, a hydrogen-fuelled fuel cell vehicle does have better powertrain efficiency, GH2 fuel would represent a very low WTW petroleum energy choice.

5. Hybrid Mode Loss Calculations

The losses that occur while operating the SPHEV are calculated in the model based on the efficiency of each component. As seen in Figure 3, there are power levels before and after each component. The efficiency of a component determines the next power level. The difference in the power levels before and after a component combined with the power flow direction are the losses of that component. For end use components like the battery, an internal resistance is used to determine both a charging and discharging loss and an internal power is calculated. For fuel conversion components, the fuel input energy is calculated based on the power output and the efficiency of the component. The hybrid mode losses are calculated separately for both operational modes due to the different energy sources for each mode. This section will cover the pump-to-wheels (PTW) energy use of the SPHEV. Three cycles to be used to determine vehicle energy consumption are the UDDS, HWFET, and US06.

The following drive cycle numbers are independent of vehicle parameters, whereas the energy and power data are specific to the test vehicle. The test parameters are displayed in Table 15. The UDDS is meant to simulate a light urban drive cycle with an average speed of 31.4 kph. The UDDS cycle is approximately 12 km in length and lasts for 1372 s. The SPHEV uses 1.71 kWh of energy at the wheels for propulsion, has a maximum propulsion power of 41.4 kW at the wheels, and an average propulsion power of 8.2 kW. The HWFET is designed to approximate highway driving with an average speed of 77.6 kph. The HWFET is 16.5 km in length and lasts for 765 s. A total of 2.15 kWh of energy is used for propulsion. The maximum propulsion power is 31.4 kW and requires an average propulsion power of 11.5 kW. The US06 drive cycle is meant to simulate more modern urban and highway driving behavior as it has more aggressive accelerations and higher top speeds than either the UDDS or the HWFET. The US06 is 12.9 km in length and lasts for 596 s. The total propulsion energy required to meet the drive trace is 2.84 kWh with a maximum propulsion power of 103.9 kW and an average propulsion power of 24.8 kW. The US06 drive cycle also has the highest decelerations of the three drive traces. The maximum deceleration power at the wheels for the US 06 is -68.0 kW. Due to the limits placed on regenerative brake energy capture by the battery, the US06 requires the use of friction brakes. This impacts the energy use of the vehicle in a negative manner, but only minimally since there is not a lot of energy to capture above -45 kW.

Table 15. Summary of drive cycle. *Vehicle specific

	Unit	UDDS	HWFET	US06
Distance	km	12	16.5	12.9
Time	s	1376	765	596
Average Speed	kph	31.4	77.6	77.7
Propulsive Energy*	kWh	1.71	2.15	2.84
Braking Energy*	kWh	-0.88	-0.26	-0.93
Maximum Power*	kW	41.4	31.4	103.9
Average Propulsive Power*	kW	8.2	11.5	24.8
Maximum Battery Regen*	kW	-28.9	-41.3	-45

5.1 Charge Depleting Mode

Charge depleting mode uses fuel energy converted at a power station, transmitted through the electrical grid, processed by a charger, converted to electrochemical energy in the battery pack, and converted back into electrical energy before the motor makes rotational energy. Each conversion process has losses that contribute to the overall vehicle energy consumption. Figure 18 displays the energy path to charge the battery pack. Since electrical energy from the grid is the primary source for charge depleting operation, its use will be followed. In this case, electrical energy is not derived from onboard fuel use, so fuel use will not be tracked. Energy use in the model is back calculated from energy use at the wheels using a series of efficiencies for the components losses. The losses presented here will be drive cycle cumulative.

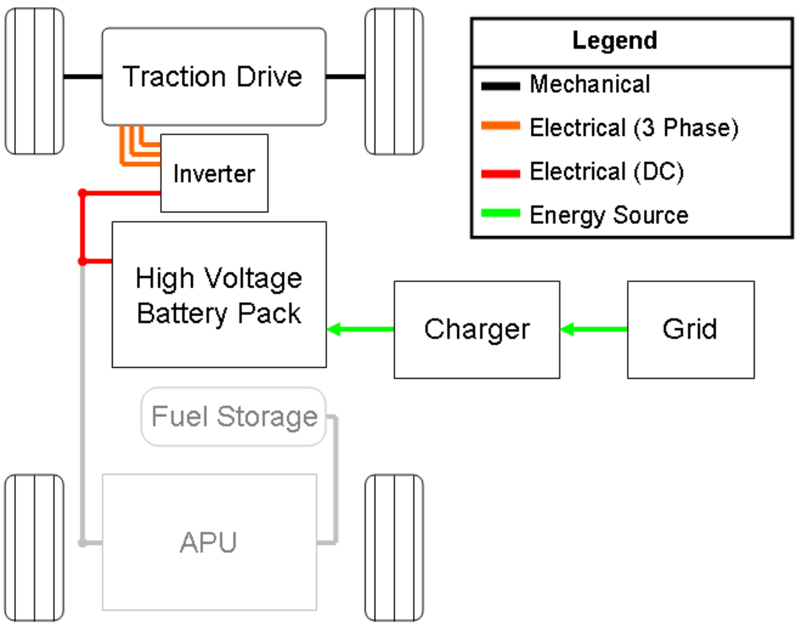

Figure 18. Offboard charging from the grid supplies the vehicle's energy needs in charge depleting mode. The APU and stored fuel are not used.

5.1.1 Calculating Powertrain Losses

For the UDDS, the total energy supplied by the battery to the powertrain is 6543.4 kJ. The individual component losses are shown in Table 16. A positive value indicates energy leaving a device. For the HWFET, the total energy supplied by the battery to the powertrain is 10261.1 kJ. The US06 cycle used 12404 kJ of energy from the battery. Figure 19 compares the energy use between the three drive cycles. The US06 is the only drive cycle where friction brakes were necessary. Because the model calculates losses as a series of efficiencies from the road to the energy source and not vice versa, powertrain regenerative brake limits pose a problem for loss calculations. The model assumes that all energy will flow from the wheels through the motor and controller onto the electrical bus. The CSF then determines the power levels for the APU, battery, and the brakes.

The brake power is then divided by the motor efficiency and drive line efficiency to calculate the power of the brakes at the wheel. The model is limited in that it does not then subtract the brake power from the wheel power going into the driveline since the driveline power has already been calculated. Therefore, brake power is an electrical equivalent dissipated power from the motor. This is to simplify loss calculations. An iterative model could find brake power at the wheels and rerun the CSF to determine losses. The iterative solution is challenging in that for each change in traction drive mechanical power, the efficiency of the motor-controller will change, so a simple subtraction is not possible to fix the error. The result of the error is that a certain portion of braking losses is shown in the motor-controller and drive line, when in fact the energy is dissipated in the brakes. This would not happen in a real vehicle since the brakes would already have subtracted the torque from what is available to the motor. The amount of energy is small, and only occurs on the US06 drive cycle where the regenerative braking cannot meet all braking requirements.

Table 16. Drive cycle energy losses by component.

		UDDS	HWFET	US06
Battery Stored Energy Change	kJ	6543	10261	12404
Battery Loss	kJ	-372	-456	-1770
Braking Loss	kJ	0	0	-72
Motor Loss	kJ	-1721	-2026	-2538
Drive Line Loss	kJ	-483	-455	-706
Road Load Loss	kJ	-3006	-6788	-6900
Accessory Loss	kJ	-960	-536	-417
Energy Balance	kJ	0	0	0

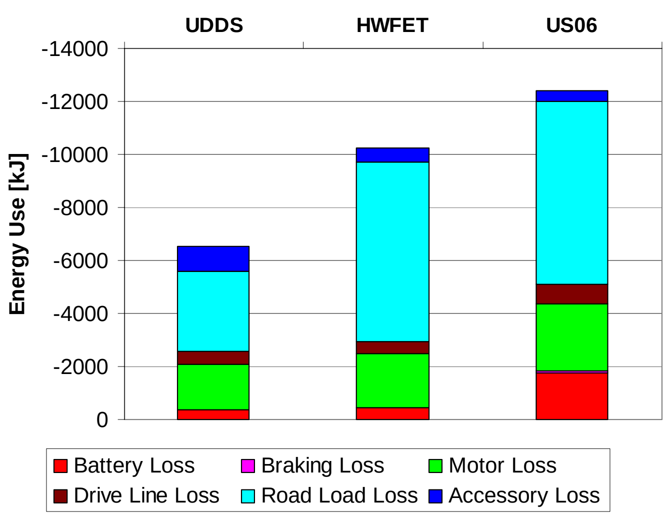

Figure 19. Energy loss for each drive cycle broken down by component.

5.1.2 Calculating Energy Use

The energy use of the SPHEV while operating in CD mode is a relatively simple matter. Since all of the energy that is used is stored onboard the vehicle in the battery, a change in the total stored energy of the battery divided by the distance driven provides the average energy use per kilometer over the drive cycle. As expected, the drive cycle with the highest losses also produced the highest energy use and likewise, the lowest losses produced the lowest energy use. Table 17 summarizes the drive cycle energy use of the SPHEV in CD mode. For each run, the initial SOC is 90% of a 16 kWh battery. The end SOC shows the resulting battery energy level at end of the drive cycle. The lowest SOC comes on the US06. This supports the US06 also having the highest total energy use and highest energy use per distance travelled. The energy use is displayed in three units. The most familiar to the consumer is the miles per gallon gasoline equivalent (mpgge) measure. For CD, the mpgge calculation uses the amount of stored energy used during the drive cycle and the amount of energy in a gallon of gasoline to create the mpgge number. This number is high for CD mode due to the high conversion efficiency of battery energy into rotational energy onboard the vehicle. The conversion of fuel energy to electrical energy is done offboard, resulting in high WTP energy use. Battery energy use represents battery stored energy not the energy at the terminals and energy use calculations are based on this value, which incorporates battery losses. A 96% efficient charger is incorporated to calculate the kJ of AC grid energy at the plug per kilometer.

Table 17. Drive cycle energy use in CD mode.

UDDS	
12	km Driven
6171	kJ Battery Terminal Energy Use
6543	kJ Battery Stored Energy Use
72	% SOC End (CD only operation)
546	kJ/km Stored Energy
137	mpgge Stored Energy
244	Wh/mi Stored Energy
262	Wh/mi AC Grid Energy
HWFET	
17	km Driven
9805	kJ Battery Terminal Energy Use
10261	kJ Battery Stored Energy Used
61	% SOC End (CD only operation)
622	kJ/km Stored Energy
120	mpgge Stored Energy
278	Wh/mi Stored Energy
290	Wh/mi AC Grid Energy
US06	
13	km Driven
10634	kJ Battery Terminal Energy Use
12404	kJ Battery Stored Energy Used
68	% SOC End (CD only operation)
962	kJ/km Stored Energy
78	mpgge Stored Energy
430	Wh/mi Stored Energy
448	Wh/mi AC Grid Energy

5.2 Charge Sustaining Mode

Charge sustaining mode uses fuel energy to meet driver demand. The battery pack acts as an energy buffer, storing and releasing energy, but staying within a narrow band of SOC. For a fuel cell powered APU, the fuel energy is converted to electrical energy inside the fuel cell stack. The unidirectional boost converter boosts the voltage to allow the fuel cell power to flow onto the high voltage bus. The traction drive system then converts the electrical energy into rotational energy. For an APU with an engine and generator, the fuel energy is converted into rotational energy in the engine, which is converted to electrical energy by the generator which is matched to the high voltage bus. The traction drive system converts the electrical energy into rotational energy. If the demand from the traction drive is not equal to the output from the APU, the battery will add or subtract energy from the bus passively due to voltage variations. Figure 20 shows the energy paths for CS operation.

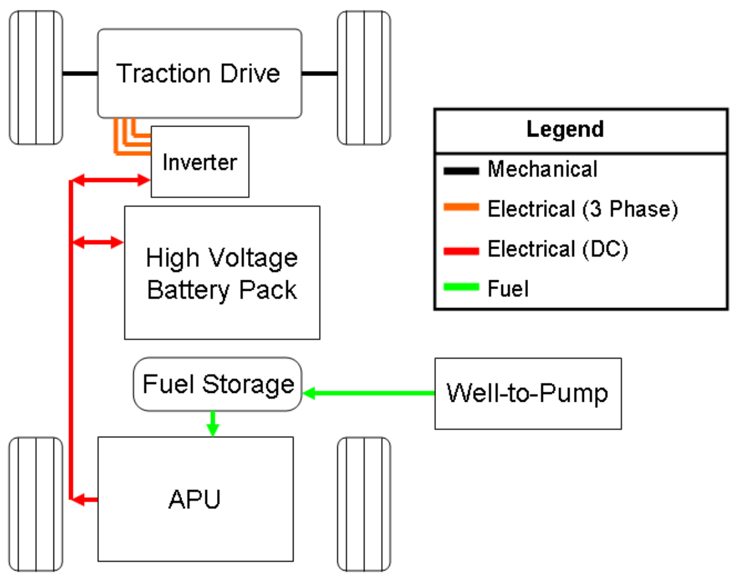

Figure 20. Fuel energy supplies the necessary energy for charge sustaining operation.

5.2.1 Calculating Powertrain Loss

Charge sustaining powertrain losses are different between the two fuel types. This is due to the different fuel converters and APU systems. Table 18 displays the losses for the SPHEV over three drive cycles. The fuel cell APU has a high conversion efficiency and therefore lower losses than the engine and generator. The battery losses will be different than CD mode operation, since less energy is being transferred into and out of the battery. The rest of the losses are component specific, and since the components are the same for CS and CD operation, the losses are the same. The CS braking loss in the HWFET that is not present in the CD cycle is due to the APU producing power during a braking event when it would not be in CD mode. Figures 21 and 22 display the energy losses for both an E85 engine generator and hydrogen fuel cell SPHEV.

Table 18. Component losses are shown over three drive cycles.

		UDDS	HWFET	US06
E85 Engine Genset Losses				
Fuel Converter Loss	kJ	-19964	-22746	-25076
Generator Loss	kJ	-692	-906	-1032
Hydrogen Fuel Cell Losses				
Fuel Converter Loss	kJ	-7313	-10027	-14611
Fuel Source Independent Losses				
Battery Loss	kJ	-255	-55	-396
Braking Loss	kJ	0	-3	-148
Motor Loss	kJ	-1721	-2026	-2538
Drive Line Loss	kJ	-483	-455	-706
Road Load Loss	kJ	-3006	-6788	-6900
Accessory Loss	kJ	-960	-536	-417

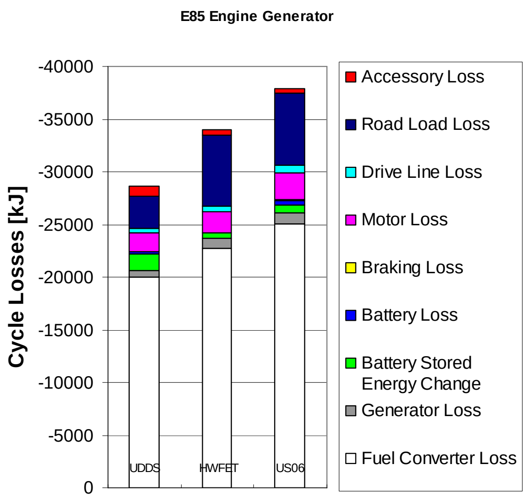

Figure 21. Energy use comparison for the E85 APU.

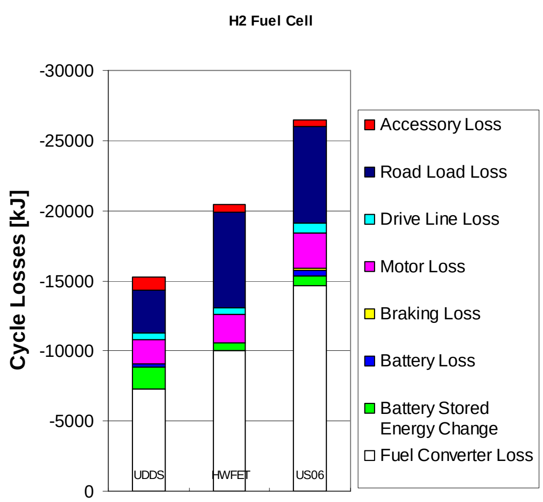

Figure 22. Energy use comparison for the H2 fuel cell APU.

5.2.2 Calculating Energy Use

The energy use of the SPHEV in CS mode is more complex than CD mode. The primary concern with CS mode is the change in SOC over the drive cycle. All tests were started with an initial SOC of 25%. For all three cycles, the ending SOC was higher than the starting SOC. The final SOC is independent of fuel type, since only the APU is changed. The fuel economy can then be calculated by subtracting this change in battery energy to the fuel energy. The error in this calculation is the string of efficiencies from fuel energy to stored battery energy. There is not an accurate way to know how much fuel energy is lost based on this model. The fuel economy would be higher if the starting and ending SOCs were the same. The PTW energy use and fuel economy over three drive cycles are listed in Table 19. The E85 powered SPHEV achieved 33.1 mpgge on the UDDS and 36.8 mpgge on the HWFET. The gaseous hydrogen fuel cell SPHEV achieved 65.2 mpgge on the UDDS and 62.0 mpgge on the HWFET. As expected, the fuel cell vehicle used less fuel energy on the UDDS compared to the HWFET due to the high efficiency at low load of the fuel cell. This is the opposite of E85 powered vehicle as the higher loads on the engine at highway speeds increase efficiency. It is important to note the distinction between the source of the energy for the energy consumption in CD mode and the energy consumption in CS mode, even though they are in the same units.

Table 19. PTW energy use.

		UDDS	HWFET	US06
E85 Engine Genset				
Fuel Energy Used	kJ	28611	34031	37940
Energy Consumption	kJ/km	2259	2030	2888
Fuel Economy	mpgge	33.1	36.8	25.9
Hydrogen Fuel Cell				
Fuel Energy Used	kJ	15267	20406	26443
Energy Consumption	kJ/km	1146	1205	1995
Fuel Economy	mpgge	65.2	62.0	37.4
Battery Energy Use - CS				
Final SOC	%	27.7	25.9	26.3
Battery Energy	kJ	-1528	-516	-726

5.3 Regenerative Braking

Regenerative braking uses the electric powertrain to convert vehicle momentum into electricity which is stored in the battery. The effects of regenerative braking are a decrease in total energy required as less energy is lost to heat in braking. The total braking energy on each drive cycle is listed in Table 15 above. For each drive cycle, the SPHEV was able to capture approximately 72% of the negative energy and store it in the battery. This 72% represents the string of losses from each component between energy at the wheels and energy stored in the battery, as well as some friction braking in the case of the US06 cycle. Regenerative brake energy capture adds apparent increased efficiency or reduced losses to the vehicle. Table 20 displays the regenerative brake energy capture.

Table 20. Regenerative brake energy capture.

		UDDS	HWFET	US06
Negative Energy	kWh	-0.88	-0.26	-0.93
Regenerative Energy in the Battery	kWh	-0.63	-0.19	-0.67
Capture	%	71.4%	72.4%	72.7%

6. Practical Considerations for Analysis

Now that the WTP energy use and petroleum energy use of the fuels has been defined and the PTW fuel use of the SPHEV for different fuels has been calculated, it is possible to combine the two to evaluate the well-to-wheel (WTW) energy use and petroleum energy use.

6.1 Calculating the Drive Cycle Average WTW Energy Use

All three energy sources will be evaluated for each drive cycle. The total energy use is divided by the total distance drive to find the average energy use. To calculate the average WTW energy use, the GREET total energy use per unit of energy used at the pump is added to the amount of fuel energy used. The WTW energy use, *WTW*, in kJ/km is calculated with Equation 20,

$$WTW = PTW + PTW \cdot (WTP) \tag{20}$$

where *PTW* is the energy use per distance in kJ/km from the model and *WTP* is the upstream energy use in MJ/MJ_{FUEL}. The GREET total energy use and WTP efficiency are listed in Table 20. The WTP efficiency can also be used to calculate WTW energy use as shown in Equation 21

$$WTW = \frac{PTW}{\eta_{WTP}} \tag{21}$$

where η_{WTP} is the WTP efficiency. The PTW and WTW values for each drive cycle and fuel are listed below in Table 21. Grid electricity has a WTP efficiency of 38% from GREET. The inclusion of a 96% efficient battery charging system drops the WTP efficiency to 36%. Even though grid electricity has the lowest WTP efficiency of 36%, the energy use of CD operation is the lowest. This is due to efficient energy storage and high conversion efficiencies from stored energy to electrical energy from the battery. This is contrasted with E85 energy consumption. With a higher WTP efficiency of 44%, the high losses of an E85 powered APU to turn fuel energy into electrical energy result in a significantly higher WTW energy consumption. The use of gaseous hydrogen as an energy carrier is more energy efficient WTP than either grid electricity or E85 at 57%. The higher APU efficiency when compared to an E85 powered APU also increase the benefits of using hydrogen. This conversion efficiency still does not compete with the battery conversion efficiency, resulting in a higher WTW energy consumption than for grid electricity.

Table 21. PTW and WTW values for each drive cycle in both CD and CS modes.

	Unit	E85 - CS	H2 - CS	Electricity - CD
Energy Use PTW				
UDDS	kJ-fuel/km	2259	1146	546
HWFET	kJ-fuel/km	2030	1205	622
US06	kJ-fuel/km	2888	1995	962
Total Energy Use WTW				
UDDS	kJ/km	5133	1996	1503
HWFET	kJ/km	4615	2099	1712
US06	kJ/km	6563	3476	2651

6.2 Calculating the Drive Cycle Average WTW Petroleum Energy Use

Similar to drive cycle average WTW energy use, the petroleum energy use is calculated using the model PTW energy use and a GREET WTW petroleum energy use per fuel energy used. The petroleum energy content data for each fuel are shown in Table 22. The WTW petroleum energy use includes both the upstream use of petroleum as well as the amount of petroleum present in the fuel. The petroleum energy use, *PEU*, calculation is shown in Equation 22,

$$PEU = PTW \cdot PEC \qquad (22)$$

where *PEC* is the petroleum energy content of the fuel and *PTW* is the vehicle energy use per kilometer. The petroleum energy use of each fuel for each drive cycle is shown in Table 22. The low petroleum energy content of hydrogen and electricity show result in very low petroleum energy use numbers.

Table 22. Petroleum energy use for each fuel and drive cycle.

	Unit	E85 - CS	H2 - CS	Electricity - CD
Petroleum Energy Use WTW				
UDDS	kJ/km	629	18	48
HWFET	kJ/km	566	19	55
US06	kJ/km	804	32	85

6.3 Calculating the Drive Cycle Average WTW GHG Emissions

The WTW GHG emissions are based on the amount of fuel used. The WTW GHG emissions per fuel energy are shown in Table UIO. These values are based on GHG gas emissions from the GREET model. The GHG emissions, *GHG*, calculation is shown in Equation 23,

$$GHG = PTW \cdot GHGF \qquad (23)$$

where *GHGF* is the GHG factor from the GREET model. The WTW GHG emissions are shown in Table 23.

Table 23. WTW GHG emissions for each fuel and drive cycle.

WTW GHG Emissions				
	Unit	E85 - CS	H2 - CS	Electricity - CD
UDDS	g CO2/km	153	109	101
HWFET	g CO2/km	137	114	116
US06	g CO2/km	195	189	179

6.4 Range Calculations

The AER is calculated using the combined energy use of city and highway drive cycles. The AER is weighted as 55% city and 45% highway. Equation 24 shows the AER calculation,

$$AER = \frac{E_{BATT}}{0.55(EU_{CITY}) + 0.45(EU_{HWY})} \tag{24}$$

where E_{BATT} is the energy available for charge depleting use in the battery, EU_{CITY} is the energy use per kilometer on the UDDS, and EU_{HWY}, is the energy use per kilometer on the HWFET. This is the reverse of the process used to size the battery. Since that is the case, the AER is calculated to be 65 km.

To meet the CDTS for vehicle range of 330 km, the vehicle must carry enough energy on board. From a full charge, the first 65 km are driven electrically, requiring fuel energy to be carried for the remaining 265 km. For CS range, the same mix of city and highway driving used to determine AER is employed. The calculation for fuel energy that must be stored on board the vehicle, E_{FUEL}, shown in Equation 25,

$$E_{FUEL} = CSR(0.55(EU_{CITY}) + 0.45(EU_{HWY})) \tag{25}$$

where CSR is the CS range. The required on board fuel energy storage for both fuels is shown in Table 24. The E85 fueled vehicle requires 24.9 L (6.6 gal) of fuel. The gaseous hydrogen fueled vehicle requires 2.9 kg of fuel.

Table 24. On board fuel energy storage requirements.

Range	km	265
E85		
Combined Energy Use	kJ/km	2155.9
Energy to meet range	MJ	571.3
Energy density of fuel	MJ/L	22.8
Total storage required	L	25.0
GH2		
Combined Energy Use	kJ/km	1172.4
Energy to meet range	MJ	310.7
Energy density of fuel	MJ/kg	107.8
Total storage required	kg	2.9

6.5 Vehicle Emissions Considerations

The model does not specifically calculate vehicle emissions from the combustion of fuels. The vehicle does not produce criteria or regulated emissions while operating in CD mode, since no fuel conversion is taking place. Likewise, no emissions are produced when operating in CS mode using a hydrogen fuel cell, as the only byproduct of operation is water vapor. The only mode with vehicle emissions is CS with E85. The combustion of E85 produces similar regulated emissions to a conventional vehicle. To meet regulated emissions standards, it is possible to operate the engine near stoichiometry with a three way catalyst. The reasoning behind the use of a minimum run time is to allow time for catalyst warmup. A catalyst heater may still be required if the engine is not run often enough to keep the catalyst warm.

Aside from vehicle regulated emissions, which represent a PTW emission cycle, WTP or upstream emissions may also be reviewed. The GREET model calculates WTP regulated emissions. The WTP regulated emissions from GREET are shown in Table 25. From this table, it can be seen that grid electricity is cleaner only in volatile organic compounds (VOC). In all other categories, grid electricity is dirtier, and has over 7 times the compounds of sulfur emissions of the next highest polluter. Compounds of sulfur are the main component associated with the production of acid rain. The WTW regulated emissions from upstream sources are shown in Table 26 for each fuel in g/km.

Table 25. Regulated WTP emissions for each fuel [17].

PTW Regulated Emissions [g/MJ] - GREET				
	RFG	E85	GH2	Electricity
VOC: Total	27.491	49.382	11.714	18.697
CO: Total	13.662	40.355	28.064	55.496
NOx: Total	39.733	116.585	69.287	227.332
PM10: Total	9.849	45.894	36.237	274.576
PM2.5: Total	3.480	15.286	18.436	72.329
SOx: Total	22.814	66.310	58.352	499.814

Table 26. WTW regulated emission from upstream sources for each fuel.

WTW Regulated Emissions from Upstream Sources [g/km]				
	RFG	E85	GH2	Electricity
VOC: Total	68.9	106.5	13.7	10.8
CO: Total	34.2	87.0	32.9	32.2
NOx: Total	99.6	251.3	81.2	131.8
PM10: Total	24.7	98.9	42.5	159.2
PM2.5: Total	8.7	33.0	21.6	41.9
SOx: Total	57.2	143.0	68.4	289.8

6.6 Stock Vehicle Energy Use

The stock vehicle realizes fuel consumption numbers as shown in Table 27. Using conventional gasoline as the energy supply, the stock vehicle attains the fuel and energy consumption listed in Table 27. The calculations performed are the same as those above. Note that the stock vehicle has a lower test mass of 1705 kg and thus requires less energy use at the wheels of each drive cycle. The stock Malibu is propelled by a 130 kW engine coupled to a four speed automatic transmission. The zero to 60 mph time of the stock vehicle is 9.5 s [26].

Table 27. Stock Malibu fuel and energy consumption.

Stock Malibu Energy Consumption			
	City	Hwy	
EPA	8.62	5.56	L/100 km
PTW	2789	1037	kJ/km
WTW	3494	1299	kJ/km
WTW PEU	2765	1028	kJ/km
WTW GHG	262	98	g CO2/km
Fuel Properties for Calculation from GREET			
LHV	116090	Btu/gal	
Total Energy	252643	MJ/MJFUEL	

6.7 Summary of Vehicle Performance

The performance of the SPHEV should be compared to the stock vehicle. The SPHEV is designed to meet all CDTS. Table 28 lists the combined results of the SPHA model and places them next to the stock vehicle. The table has as simple color system: red for below stock levels, yellow for a marginal improvement, and green for an improvement over stock. E85 provides a 19% decrease in city driving PTW energy use, but an almost 100% increase in highway PTW energy use. The WTW energy use for E85 is higher than the stock vehicle. The petroleum energy consumption for the E85 powered SPHEV is a mere 23% of that of the stock vehicle, representing a 77% reduction in WTW petroleum energy use. The gaseous hydrogen city PTW energy use is 59% less than the stock vehicle while the highway PTW energy use is 16% higher than in the stock vehicle. The city WTW energy use while using gaseous hydrogen is 43% less than the stock vehicle. The highway WTW energy use is 62% greater (Note that series hybrid vehicle architectures are not particularly efficient for steady highway cycles). The largest benefit of gaseous hydrogen is seen in the WTW petroleum energy use, 98% highway reduction and 99.5% city reduction. In CD mode, the efficiency of the battery system provides a PTW energy use reduction of 80% in the city and 40% on the highway. Like gaseous hydrogen, grid electricity also provides a significant reduction in WTW energy use for the city, 42%. The highway energy use for grid electricity has the lowest increase, at 26%. The WTW petroleum reductions in the city and highway cycles for grid electricity are 98% and 95% respectively. The increase of energy use in both CS and the CD mode indicate a deficiency of the SPHEV. The inclusion of a parallel energy path for the engine powered APU would most likely increase highway fuel economy. GHG emissions are also tabulated. Even though CD mode has a high WTP GHG emission factor, the low energy use keeps total GHG emissions low. The stock vehicle's efficient highway operation results in low GHG emissions. With a grid mix less dependence on fossil energy sources, grid electricity, with its high PTW energy efficiency, could have lower GHG emissions than the conventional vehicle. CD mode also points to the future of battery electric vehicle (BEV) energy use and emissions.

Table 28. Combined results compared to the stock vehicle.

			E85	GH2	Electricity	Stock
PTW Fuel Energy Consumption	City	kJ/km	2259	1146	546	2789
	Hwy	kJ/km	2030	1205	622	1037
WTW Fuel Energy Consumption	City	kJ/km	5133	1996	1440	3494
	Hwy	kJ/km	4615	2099	1640	1299
WTW Petroleum Energy Consumption	City	kJ/km	629	18	48	2765
	Hwy	kJ/km	566	19	55	1028
WTW GHG Emissions	City	g CO2/km	155	109	101	262
	Hwy	g CO2/km	139	114	116	98

6.8 Utility Factor

The utility factor (UF), explained by Duoba et al., is "calculated using the National Highway Transportation Survey (NHTS) with the most recent 2001 data…It represents a mileage-weighted probability that the first x-miles driven per day can be driven in charge-depleting (or EV) mode" [24]. The UF allows for the combination of CD and CS fuel consumptions. The UF for a PHEV with a 65km (40 mi) AER is 0.62. This indicates that 62% of vehicle trips would use only the AER and no fuel. The formula for using the UF from Duoba et al. is shown in Equation 26,

$$FC_{UF-WEIGHTED} = UF \cdot FC_{CD} + (1 - UF)FC_{CS} \tag{26}$$

where $FC_{UF\text{-}WEIGHTED}$ is the weighted fuel consumption, FC_{CD} is the CD fuel consumption, and FC_{CS} is the CS fuel consumption. The results from the application of the UF are shown in Table 28.

Table 29. Utility factor weighted fuel economies.

		E85	GH2	Electricity
City	kJ/km	2259	1146	546
Hwy	kJ/km	2030	1205	622
Combined	kJ/km	2156	1172	580
UF		0.62	0.62	
Combined-Weighted	kJ/km	1557	947	
Combined-Weighted	mpgge	48.0	78.8	

Over the vehicle life of 150,000 miles with electrical costs of $0.10/kWh, the consumer could expect to spend $2,550 on electrical refueling. With $4.00/gal E85, the remaining 57,000 miles cost $6,560 for a total cost to the consumer of $9,110 over the life of the vehicle. This is contrasted to $17,300 running the SPHEV on E85 alone for a savings of over $8,000 with grid energy use.

7. Conclusion

This paper presents a model of a plug-in hybrid electric vehicle for use in evaluating different technologies and sizing components. The literature review covers relevant publications in conferences, journals and government research institutes. The need for this paper is evident in the lack of simplified, non-commercial models for the evaluation of plug-in hybrid technology and component sizing. The background for the base vehicle is derived from the EcoCAR request for proposal. The model is then explained. The results of the model, in combination with Argonne National Lab's greenhouse gas, regulated emissions, and energy use in transportation (GREET) model allow for the assessment of pump-to-wheel (PTW) and well-to-wheel (WTW) energy use, petroleum energy use and greenhouse gas (GHG) emissions of different fuels. The evaluation of petroleum energy use is important in today's political and economic climate.

The series plug-in hybrid electric vehicle (SPHEV) is capable of operating in a charge depleting mode where it uses only grid electricity stored in a battery pack to operate the vehicle. This mode allows for an increase in vehicle efficiency and a decrease in petroleum energy consumption. The fuel economy of a vehicle with an all electric range (AER) is weighted using a utility factor (UF). The combined, state of charge (SOC) corrected, UF weighted fuel economy of the two fuels are as follows: 50.3 mpgge for E85 and 82.6 mpgge for gaseous hydrogen. For charge sustaining operation, the SPHEV achieves a combined, unadjusted, gasoline equivalent fuel consumption of 6.8 L/100km (34.8 mpgge) using E85 and 3.7 L/100km (63.7 mpgge). In charge depleting operation, the SPHEV used 604 kJ/km (270 Wh/mi) of AC grid electricity. Operation using either the fuel cell or charge depleting mode results in a zero emission vehicle (ZEV) meeting the requirements for a CARB Type III classification [14].

Gaseous hydrogen provides many benefits over E85 in the SPHEV, such as better fuel economy, lower WTW and PTW energy use, and lower GHG emissions. It also out performs the stock vehicle in many of these categories including a WTW petroleum energy use reduction of 98% on the highway and 99.5% in the city. The drawbacks of the gaseous hydrogen include cost, difficult packaging of the fuel storage system, and the temperature sensitivity of the fuel cell stacks. An E85 capable SPHEV offers lower cost technology, a vehicle energy consumption reduction for city driving, and the capability of offsetting petroleum with grid electricity. E85 offers a charge sustaining petroleum reduction of 77% in the city and 45% on the highway. In this way, E85 provides some of the benefits of hydrogen without the cost and complex systems. The SPHEV provides an all electric range of 65 km (40 mi) which satisfies greater than 60% of commutes in the US [24]. During this, the vehicle uses less than 5% of the petroleum energy of the stock vehicle, and reducing city driving GHG emissions by more than 60% due to its high efficiency powertrain. The SPHEV does not use the auxillary power unit during charge depleting operation as a blended plug-in hybrid would. This reduces the number of engine starts, emissions, as well as fuel and petroleum use which lowers operating costs. The SPHEV design reduces WTW petroleum energy use and can decrease GHG emissions, in addition to meeting the requirements set by the EcoCAR organizers.

The stock Malibu accelerates from zero to 60 mph in 9.5 s [26]. The SPHEV is approximately of the same performance level with a zero to 62 mph (100 kph) time of 10 s. The PTW energy use of the SPHEV indicates that it is possible for it to achieve lower energy consumption for city driving, but does not do so using E85. Only grid electricity uses less PTW energy on the highway than the stock vehicle. This is due to the lower conversion efficiency of fuel energy into rotational energy at the wheels of the SPHEV and is one of the shortcomings of the series architecture. More advanced and efficient fuel conversion is necessary for increased PTW energy efficiency. Both gaseous hydrogen and grid electricity provide increased PTW efficiency.

Gaseous hydrogen competes with the stock vehicle in highway energy use and is considerably less for city driving. The high energy inputs for the alternative fuels increase the WTW highway energy consumption of the SPHEV to greater than the WTW energy consumption of the stock vehicle. The stock vehicle is less efficient in city driving, and the advanced technology fuel cell vehicle is capable of reduced WTW energy use, petroleum energy use and GHG emissions. Using similar technology to the stock vehicle, the E85 powered SPHEV is not capable of reducing WTW energy use due to the inherent inefficiency of the series architecture, the high input energy of the fuel, and the low conversion efficiency of fuel into electricity from the engine and generator. All fuels are capable of reduced WTW petroleum energy use compared to the stock vehicle due to the low content of petroleum in the fuels as well as low petroleum use in their production.

The low energy use of the SPHEV operating on grid electricity provides a vehicle capable of reductions in all categories except highway WTW energy use and highway WTW GHG emissions. The reductions are due to the battery storing and releasing energy efficiently along with a motor-controller also efficiently converting electrical power to power at the wheels. The upstream energy used to produce the electricity that is stored in the battery is not efficient enough when combined with the vehicle energy use to achieve reductions in highway WTW energy use. Improvements made to generation of grid electricity and distribution would decrease the WTW energy use of the SPHEV in charge depleting mode and position it competitively with the stock vehicle. A transition of grid generated electricity from fossil sources to renewable sources would decrease the upstream GHG emission factor of grid electricity which, combined with the low energy use of the SPHEV in charge depleting mode, would place the SPHEV below the stock vehicle in GHG emissions.

In combination with the low energy use in charge depleting mode of the SPHEV, a hydrogen powered fuel cell offers improved city PTW and WTW energy use compared to the stock vehicle. The E85 powered vehicle is less efficient in all but PTW city energy use, but does provide significant reductions in WTW petroleum energy use and city GHG emissions.

References

[1]. "US Crude Oil Supply & Distribution." Energy Information Administration. 2008. http://tonto.eia.doe.gov/dnav/pet/pet_sum_crdsnd_adc_mbbl_m.htm

[2]. Bob Lutz, "Lutz promotes energy conservation, criticizes politicians", SAE Automotive Engineering, Feb. 2008, page 30.

[3]. M. Bly, "Hybrid Technologies", Roundtable Proceedings from 2007 Challenge Bibendum, http://www.challengebibendum.com/challengeBib/document.DocumentRepositoryServlet?codeDocument=3810&codeRepository=MICHA&codeRubrique=RT2007DET

[4]. Pesaran, A., Markel, T., Tataria, H., Howell, D. "Battery Requirements for Plug-In Hybrid Electric Vehicles – Analysis and Rationale." Electric Vehicle Symposium 23. 2007.

[5]. Belt, J. "Plug-In Hybrid Vehicle Testing Procedures." Electric Vehicle Symposium 23. 2007.

[6]. Kromer, M. "Electric Powertrains: Opportunities and Challenges in the US Light-Duty Vehicle Fleet." Massachusetts Institute of Technology. 17 May 2007. http://dspace.mit.edu/handle/1721.1/40372

[7]. Knipping, E., Duvall, M., Clark, C., Tonachel, L. "Environmental and Electric-Sector Assessment of Plug-In Hybrid Electric Vehicles: Air Quality." Electric Vehicle Symposium 23. 2007.

[8]. "Progress Report for Energy Storage Research and Development." Office of FreedomCAR and Vehicle Technologies. United States Department of Energy. January 2007.

[9]. Markel, T., Simpson, A. "Plug-In Hybrid Electric Vehicle Energy Storage System Design." Advanced Automotive Battery Conference. May 2006. http://www.osti.gov/bridge/product.biblio.jsp?query_id=0&page=0&osti_id=883666

[10]. Rousseau, A. "Plug-In HEV Component Requirements for Mid-size Car and Mid-size SUV." Advanced Vehicle Technology Analysis and Evaluation Activities. *FY 2006 Annual Report*. Argonne National Lab.

[11]. Boyd, S., Lee, J., Nelson, D. "A Simplified Battery Model for Hybrid Vehicle Technology Assesment." Society of Automotive Engineers. 2007. 2007-01-0301.

[12]. "EcoCAR Media Announcement." EcoCAR. 6 December 2007. http://www.ecocarchallenge.org/docs/EcoCAR_press_release.pdf

[13]. "EcoCAR Request for Proposal." EcoCAR. 2007. http://www.ecocarchallenge.org/docs/ecocar_rfp.pdf

[14]. "California Exhaust Emission Standards and Test Procedures for 2005 and Subsequent Model Zero-Emission Vehicles, and 2001 and Subsequent Model Hybrid Electric Vehicles, in the Passenger Car, Light-Duty Truck and Medium-Duty Vehicle Classes." California Air Resources Board. 19 December 2003. http://www.arb.ca.gov/msprog/levprog/cleandoc/clean_2003_zev_tps.pdf

[15]. "Test Car List Data." US Environmental Protection Agency. 2008. http://www.epa.gov/OMS/cert/mpg/testcars/database/08tstcar.csv

[16]. Johnson, K., Pawlowski, R., Diaz, M., Nelson, D. "A Proposal for the Participation in EcoCAR: The NeXt Challenge." Virginia Tech. 1 March 2008.

[17]. "The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model." Argonne National Lab. 8 May 2008. http://www.transportation.anl.gov/software/GREET/

[18]. Larminie, J., Lowry, J. Electric Vehicle Technology Explained. Hoboken, NJ: John Wiley and Sons. 2003.

[19]. "USBAC Goals for Advanced Batteries for EVs." US Advanced Battery Consortium. http://www.uscar.org/commands/files_download.php?files_id=27

[20]. Nam, E., Sorab, J. "Friction Reduction Trends in Modern Engines." Society of Automotive Engineers. 2004. 2004-01-1456.

[21]. "GM Announces Two New Fuel Efficient Engines." GM Media. 15 May 2008. http://media.gm.com/servlet/GatewayServlet?target=http://image.emerald.gm.com/gmnews/viewpressreldetail.do?domain=827&docid=45710

[22]. "The E-Flex Drive System – What It Is and How It Works." Chevrolet. 2007. http://www.chevrolet.com/pop/electriccar/2007/process_en.jsp

[23]. "Challenge X Rules." Argonne National Lab. 2007. http://www.challengex.org/sproot/sproot/Challenge X Students/Challenge X Rules/cxy4 comp rules 11_20_07 - editCK.pdf

[24]. Duoba, M., Carlson, R., Wu, J. "Test Procedure Development for 'Blended Type' Plug-In Hybrid Vehicles." Society of Automotive Engineers. 2008. 2008-01-0457.

[25]. "Powertrain System Analysis Toolkit." Argonne National Lab. http://www.transportation.anl.gov/software/PSAT/

[26]. Riches, Erin. "Revitalized Malibu Takes on Accord and Camry." Edmunds Inside Line. 1 January 2008. http://www.edmunds.com/insideline/do/Drives/Comparos/articleId=124091

Appendix A. Model Parameters

Description	Variable	Units	Value
Initial Conditions			
Reference mass of base vehicle	refmas	kg	1705
Test mass	vehiclemass	kg	1900
0th order road load coefficient	F0	N	93.45
1st order road load coefficient	F1	N/(m/s)	3.58
2nd order road load coefficient	F2	N/(m/s)^2	0.42
Accessory load	accload	W	700
Drive line efficiency	Dleff	%	0.95
Rotational mass factor	mrotate		1.04
Rotations of rotor per vehicle speed	NoverV	rpm/kph	84.375
Wheel diameter	WD	m	0.64
Grade	grade	%	0
Mode (CS,CD)	Mode		1,3
Lower limit for CS SOC	SOCCSLow		0.2
Upper limit for CS SOC	SOCCSHi		0.3
Minimum APU runtime	minruntime	s	60
Battery energy capacity	b	J	57600000
SOC at start of analysis	intialSOC		0.9
Open circuit voltage at 100% SOC	OCV100	V	360
Open circuit voltage at 0% SOC	OCVzero	V	312
Motor Controller Function			
Copper loss	kc		0.26
Iron loss	ki		0.01
Windage loss	kw		5.00E-06
Constant loss	C		800
Control Strategy Function			
Minimum APU power	Pmin	W	7000
Maximum APU power	Pmax	W	60000
Maximum regenerative brake power	Pregen	W	-45000
Battery Model			
Discharge resistance	dR	Ohms	0.25
Charge resistance	cR	Ohms	0.25
Engine Efficiency			
Displacement	Disp	L	1.4
Indicated thermodynamic efficiency	Etherm		0.39
Friction mean effective pressure	fmep	kPa	170
Generator efficiency	geta		0.92
Minimum engine speed	rpm_base	rpm	1300
Maximum torque at base speed	torque_base_peak	N	120
Torque rising rate	Torque_rising_rate	Nm/rpm	0.04
Peak torque	Peak_torque	Nm/rpm	175
Fuel Cell Efficiency			
Boost converter efficiency	boost		0.96
Power input points	x	% load	[0,10,40,100]
Efficiency output points	y		[0, .55, .52, .35]

Appendix B. Model Code

Below is found the code for the main m-file, “MODEL.m”.

```
%Vehicle power simulation
%created by Kurt Johnson
%Started Oct 28, 2007

%Conventions
%Positive engine power is generated power
%Battery power being drawn from the battery is positive -
opposite Cobasys

clear all; clc;

%Vehicle Characteristics
crr = 0.0079; %Nelson modified 0.0056 from RFP
cd = 0.37; %Nelson modified 0.33 from RFP
fa = 2.209; %frontal area [m^2}
refmass = 1705; %[kg] Original coefficient mass
vehiclemass = 1900; %[kg]
Battmass = 0; %[kg] Additional battery mass penalty
FCmass = 0; %[kg] Additional fuel converter mass penalty
m = vehiclemass + Battmass + FCmass; %[kg]
F0 = m/refmass*93.45; % [N]
F1 = m/refmass*3.58; % [N/(m/s)]
F2 = 0.42; % [N/(m/s)^2]
accload = 700; %[W] Accessory load
DLeff= 0.95; %Drive line efficiency
mrotate=1.04; %rotating mass multiplier
NoverV=13500/160; %rotor rpm/kph top speed
WD=0.64; %wheel diameter in meters
grade=0; % percent grade



%More powertrain limits stored in control strategy mfile
Mode=1; %1 for CS, 3 for CD
SOCCSLow = 0.2;
SOCCSHi = 0.3;
SOCCSTarget = (SOCCSLow + SOCCSHi) / 2;
minruntime=60; %[s] Minimum time the fuel converter is on
(set lower for fuel cell)
b=16*3600000; %battery capacity [J] kW-hr * conv
initialSOC=.25; %SOCCSTarget; %initial SOC
OCV100=360; %Open Circuit Voltage @ 100% SOC
```

```
OCVzero=312; %Open Circuit Voltage @ 0% SOC

%load drive cycle from Excel file

type = 'UDDS';
%edit range
data = xlsread('DriveCycles_Scaled.xls',type, 'A4:B1376');
multi=1.609344; %speed multiplier from mph to kph
run=1; %run cycle this many times - whole numbers only
Time = data(:,1); %[s]
Speed = multi*data(:,2); %[kph]
V = Speed.*1000/3600; %[m/s]
time=Time;
speed=Speed;

%Allow for back to back runs of the same drive cycle
without resetting
if run > 1
    for tick=1:(run-1)
        time=cat(1,time,(Time+(tick.*length(Time))));
        speed=cat(1,speed,Speed);
    end
    v = speed.*1000/3600;
else
    time=Time;
    speed=Speed;
    v=V;
end


%initialize variables
INIT=zeros(1,length(time));
Energy=INIT;
Epos=INIT;
Eneg=INIT;
Pout=INIT;
Ppos=INIT;
Pneg=INIT;
Pbattint=INIT;
Pfc=INIT;
Pbatt=INIT;
Pbattpos=INIT;
Pbattneg=INIT;
Energybatt=b*initialSOC*ones(1,length(time));
Pbrake=INIT;
Pregen=INIT;
FCTime=INIT;
```

```
FCbit=INIT;
Pmax=INIT;
Pmin=INIT;
SOC=initialSOC*ones(1,length(time));
mode=INIT;
MCeff=INIT;
Pbus=INIT;
Pmot=INIT;
torq=INIT;
DLloss=INIT;
Motorloss=INIT;
Volts=(OCVzero + (OCV100-
OCVzero)*initialSOC)*ones(1,length(time));
OCV=Volts;
Battloss=INIT;
mrpm=INIT;
fuelenergy=INIT;
FCeta=INIT;
FCloss=INIT;
bias=INIT;
EngRPM=INIT;
Teng=INIT;
Peng=INIT;
GenLoss=INIT;
Brakingloss=INIT;
RoadLoadLoss=INIT;
accyengy=INIT;
PMOT=INIT;

for t=1:(time(end)) %Start calculation

    step = time(t+1)-time(t); %Calculate time step

    Fdc = mrotate * m * (v(t+1)-v(t))/step; %Calculate the
force due to the drive cycle (using inertial mass factor
for rotating mass)
    vavg=(v(t+1)+v(t))/2; %Calculate step average velocity
    G = grade/sqrt(100^2 + grade^2); %Calculate the % of
vehicle weight that is acting as drag on grade
    weight = m * 9.81; %[N]
    Fg = G * weight; %Calculate grade force
    Pdc = Fdc*vavg + Fg*vavg; %Calculate the power
requirement due to drive cycle and grade


    %calculate power requirement at wheels in [W]
%     Pout(t+1) = Pdc + RoadLoad(vavg, crr, cd, fa, m);
```

```
    Pout(t+1) = Pdc + RoadLoadF(vavg, F0, F1, F2);  %Add
road load to power requirement from drive cycle and grade
    RoadLoadLoss(t+1) = -RoadLoadF(vavg, F0, F1, F2)*step +
RoadLoadLoss(t); %Calculate power loss due to road load


    if t>0 %calculate total, positive, and negative energy
at the wheels
        Energy(t+1) = Energy(t) + Pout(t+1)*step; %[W-s]
        if Pout(t+1) > 0
            Ppos(t+1) = Pout(t+1);
            Epos(t+1) = Pout(t+1) * step + Epos(t);
            Eneg(t+1) = Eneg(t);
        else
            Pneg(t+1) = Pout(t+1);
            Eneg(t+1) = Pout(t+1) * step + Eneg(t);
            Epos(t+1) = Epos(t);
        end
    end


    if Pout(t+1) > 0 %calculate motor output power and
drive line efficiency
        Pmot(t+1) = Pout(t+1)/DLeff;
        DLloss(t+1)=step*(Pout(t+1)-Pmot(t+1))+DLloss(t);
%[J]
    else
        Pmot(t+1) = Pout(t+1)*DLeff;
        DLloss(t+1)=step*(Pout(t+1)-Pmot(t+1))+DLloss(t);
%[J]
    end

    mrpm(t+1) = vavg*3.6*NoverV; %calculate rotor speed for
acceleration

    %call motor efficiency function
    MCOut=MotorController(Pmot(t+1),mrpm(t+1));
    MCeff(t+1)=MCOut(1);
    torq(t+1)=MCOut(2);
    overdemand=MCOut(3);



    %PMOT is the electrical input power to the motor
    if Pout(t+1) > 0
        PMOT(t+1) = (Pmot(t+1)/MCeff(t+1)); %[W]
```

```
        Motorloss(t+1)=(Pmot(t+1)-PMOT(t+1))*step +
Motorloss(t); %(Pmot(t+1)-Pmot(t+1)/MCeff(t+1))*step +
Motorloss(t); %[J]
    else
        PMOT(t+1) = (Pmot(t+1)*MCeff(t+1)); % [W]
        Motorloss(t+1)= (Pmot(t+1)-PMOT(t+1))*step +
Motorloss(t); %(-Pmot(t+1)*MCeff(t+1)+Pmot(t+1))*step +
Motorloss(t); %[J]
    end

    %Pbus is power required at the DC bus
    Pbus(t+1) = PMOT(t+1) + accload;

    %Sum energy used by accessories
    accyengy(t+1) =  -accload*step + accyengy(t);

    mode(t)=Mode;

    %begin "control strategy" - determine where the power
is coming from

CSOut=ControlStrat(Pbus(t+1),Mode,SOC(t),FCTime(t),SOCCSLow
, SOCCSHi, SOCCSTarget);
    Pfc(t+1)=CSOut(1);
    Pbatt(t+1)=CSOut(2);
    Running=CSOut(4);
    Pmax(t+1)=CSOut(5);
    Pmin(t+1)=CSOut(6);
    bias(t+1)=CSOut(7);
    %end "control strategy"

    if Pout(t+1) < 0
        Pbrake(t+1)=CSOut(3);  %/MCeff(t+1)/DLeff;  --- use
to find actual brake force.  Removed when found to be cause
of error.
        Brakingloss(t+1) = Pbrake(t+1)*step+Brakingloss(t);
    else
        Pbrake(t+1)=Pbrake(t);
        Brakingloss(t+1)=Brakingloss(t);
    end


    %set fc run flag
    if FCTime(t)==0  && Pfc(t)==0
        if Running==1
            for z=1:minruntime
                FCTime(t+z)=1;
```

```
            end
        end
    end

    %BATTERY CALCS - positive energy is energy required of
the battery

Outputbatt=BattModel(Pbatt(t+1),SOC(t),OCVzero,OCV100,b,ste
p);
    Volts(t+1)=Outputbatt(1);
    Pbattint(t+1)=Outputbatt(2);
    Battloss(t+1)=step*(Pbatt(t+1)-
Pbattint(t+1))+Battloss(t);
    Energybatt(t+1)=Energybatt(t)-(Pbattint(t+1)*step);
    SOC(t+1) = Outputbatt(3);
    OCV(t+1) = Outputbatt(4);


    %Fuel Converter calculations
    if Pfc(t+1) > 0
%          FCout = EGENeta(Pfc(t+1));
%          FCeta(t+1) = FCout(1);
%          EngRPM(t+1) = FCout(2);
%          Teng(t+1) = FCout(3);
%          Peng(t+1) = FCout(5);

        FCeta(t+1)=FCeff(Pfc(t+1),Pmax(t+1));

fuelenergy(t+1)=Pfc(t+1)/FCeta(t+1)*step+fuelenergy(t);
%[J] %Engine use Peng, FC use Pfc
        FCloss(t+1) = (Pfc(t+1) - Pfc(t+1)/FCeta(t+1))*step
+ FCloss(t);  %Engine use Peng, FC use Pfc
%          GenLoss(t+1) = Pfc(t+1)-Peng(t+1) + GenLoss(t);
    else
        FCeta(t+1) = 0;
        fuelenergy(t+1) = fuelenergy(t);
        FCloss(t+1) = FCloss(t);
        GenLoss(t+1) = GenLoss(t);
    end




    % Mode change calculations
    if Mode == 3
        if SOC(t+1) < SOCCSTarget
            Mode = 1;
```

```
        end
    end
    if Mode == 4
        if SOC(t+1) < SOCCSTarget
            Mode = 2;
        end
    end
    if Mode == 1  || Mode == 2
        if SOC(t+1) > SOCCSHi
            Mode = mode(1);
        end
    end


end

for a=1:length(time)
    FCbit(a)=FCTime(a);
end



%Matlab Plots
figure(1)
plot(time,speed)
title('Speed [kph]')
xlabel('Time [s]')
figure(2)
plot(time, Energy./3600000)
title('Energy use at wheels [kW-hr]')
xlabel('Time [s]')
figure(3)
plot(time, Pfc./1000)
title('Fuel Converter Power [kW]')
xlabel('Time [s]')
figure(4)
plot(time, Pbatt./1000)
title('Battery Power [kW]')
xlabel('Time [s]')
figure(5)
plot(time, SOC)
title('Battery SOC [kW-hr]')
xlabel('Time [s]')
figure(6)
plot(time, Pout./1000)
title('Power at wheels [kW]')
xlabel('Time [s]')
```

```
figure(7)
plot(time, Pbrake./1000,'.')
title('Brake Power [kW]')
xlabel('Time [s]')
figure(8)
plot(time, Pbus./1000)
title('DC Bus Power [kW]')
xlabel('Time [s]')
figure(9)
plot(time, MCeff,'.')
title('MC eta')
xlabel('Time [s]')
figure(10)
plot(mrpm,torq, '.')
title('Motor Torque at Motor RPM')
xlabel('Motor RPM')
figure(11)
plot(time,Volts)
title('Battery Voltage')
xlabel('Time [s]')
figure(12)
plot(time,OCV)
title('Open Circuit Voltage')
xlabel('Time [s]')
figure(13)
plot(time,bias)
title('SOC Bias Coefficient')
xlabel('Time [s]')
figure(14)
plot(time,Peng./1000)
title('Engine Power [kW]')
xlabel('Time [s]')
figure(15)
plot(time,FCeta)
title('Fuel Converter eta')
xlabel('Time [s]')



%Write XLS file
M1={'Time [s]','Speed [kph]','Energy [kW-hr]','Pos Energy
[kW-hr]','Neg Energy [kW-hr]','Road Load [kW]','Motor Mech
Power [kW]','Motor Torque [Nm]','Motor Controller
Eff','Motor Elec Power [kW]','DC Bus Power','Bias','Fuel
Converter Power Out [kW]','Battery Demand Power
[kW]','Battery Internal Power [kW]','OCV [V]','Voltage
[V]','SOC [%]','Battery Stored Energy [kW-hr]','Braking
```

```
Power [kW]','Mode','FCTime','Max Power [kW]','Min Power
[kW]','FC eta','Engine Power [kW]','Engine Torque
[Nm]','Fuel Energy Used [kJ]','Fuel Converter Loss
[kJ]','Generator Loss [kJ]','Battery Loss [kJ]','Braking
Loss [kJ]','Motor Loss [kJ]','Drive Line Loss [kJ]','Road
Load Loss [kJ]','Accessory Loss [kJ]'};
M2=cat(2,time,speed,Energy'./3600000,Epos'./3600000,Eneg'./
3600000,Pout'./1000,Pmot'./1000,torq',MCeff',PMOT'./1000,Pb
us'./1000,bias',Pfc'./1000,Pbatt'./1000,Pbattint'./1000,OCV
',Volts',SOC'.*100,Energybatt'./3600000,Pbrake'./1000,mode'
,FCbit',Pmax',Pmin',FCeta',Peng'./1000,Teng',fuelenergy'./1
000,
FCloss'./1000,GenLoss'./1000,Battloss'./1000,Brakingloss'./
1000,Motorloss'./1000,DLloss'./1000,RoadLoadLoss'./1000,acc
yengy'./1000);
M3={'F0','F1','F2','Mass','Accessory Load','DL eta','Min
Run Time','Battery Capacity [kW-hr]','Velocity
Multiplier','# Times Cycle Repeated'};
M4=cat(2,F0,F1,F2,m,accload,DLeff,minruntime,b/3600000,mult
i,run);
now = datestr(clock,30);
x=[type '_' now];
warning off MATLAB:xlswrite:AddSheet
xlswrite(x,M1,'Data' ,'A5');
xlswrite(x,M2,'Data' ,'A6');
xlswrite(x,M3,'Data','A1');
xlswrite(x,M4,'Data','A2');
```

Appendix C. Called Functions

Below is found the code for each called function.

Road Load Function

```
function[Pout]=RoadLoadF(v, F0, F1, F2)

Frl = F0 + F1*v + F2*v^2;
Prl = Frl * v;



Pout = Prl;
```

Motor-Controller Efficiency Function

```
function[Output]=MotorController(Preq,rpm)

kc = 0.26; %Copper loss
ki = 0.01; %Iron loss
kw = 5E-6; %Windage loss
C = 800;   %Constant loss

%rpm is the rotor rpm at the average velocity for the
timestep.

overdemand = 0;
Powerlim=98200; %power limit of the motor in [W]

if Preq > Powerlim
    overdemand = Preq-Powerlim;
    Preq = Powerlim;
end

w=rpm*(2*pi/60); %rpm to rad/s
T=abs(Preq/w);   %calculate torq from the required power

eta = (T*w)/(T*w+kc*T^2+ki*w+kw*w^3+C);

if rpm == 0
    eta = 0;
end

 if eta < .20 && Preq > 0
     eta = .20;
 end

 Torq=Preq/w;

Output = [eta,Torq,overdemand];
```

Control Strategy Function

```
function[Output]=ControlStrat(Preq,Mode,SOC,Run,Lo,Hi,Trgt)

%April 2, 2008 Version

%initialize variables
NewRun=0;
Pbrake=0;
Pbatt=0;
Pfc=0;

range = Hi - Lo;


%vehicle characteristics
Pmin1 = 7000; %[W] min engine power
Pmax1 = 60000; %[W] max engine power
Pmin2 = 20000; %[W] min engine power
Pmax2 = 60000; %[W] max engine power
Pregen = -45000; %[W] max regen power of battery


if Mode == 1
    Pmin=Pmin1;
    Pmax=Pmax1;
elseif Mode == 2
    Pmin=Pmin2;
    Pmax=Pmax2;
elseif Mode == 3
    Pmin=Pmin1;
    Pmax=Pmax1;
    Run = -1;
elseif Mode == 4
    Pmin=Pmin2;
    Pmax=Pmax2;
    Run = -1;
end


if SOC > Hi && Run < 1
    Run = -1;
end

if (Mode == 1 || Mode == 2) && SOC > Hi
    Pregen = 0;
elseif SOC > 0.95
```

```
    Pregen = 0;
end



if SOC < Lo    %charge battery when lw
    Run=1;
end
if SOC < (Lo-0.05)    %charge battery at max when very low
    Run=1;
    Pmin=Pmax;
end


%BEGIN CSF%

if Run>0            %%%%%%%FC Req'd Mode%%%%%%%%%%%%  MODE
THREE
    if Preq > 0
        if Preq > Pmax
            Pfc=Pmax;
            Pbatt=Preq-Pfc;
        elseif Preq > Pmin
            Pfc = Preq;  %possibility of charging battery
here based on battery energy used
            Pbatt = 0;
        else
            Pfc= Pmin;
            Pbatt=Preq-Pfc;
        end
    elseif Preq < 0
        Pfc = Pmin;
        if Preq - Pfc > Pregen
            Pbatt=Preq-Pfc;
            Pbrake=0;
        else
            Pbatt = Pregen;
            Pbrake = -(Pregen-(Preq-Pfc));
        end
    end

elseif Run < 0          %%%%%%Charge Depleting
Mode%%%%%%%%%%%%  MODE ONE
    if Preq > 0
        Pfc=0;
        Pbatt = Preq;
    else
```

```
        Pfc=0;
        if Preq > Pregen
            Pbatt = Preq;
        else
            Pbatt = Pregen;
            Pbrake = Preq-Pregen;
        end
    end

else                   %Charge Sustaining Hybrid Mode%
    if Preq > 0
        if Preq > Pmax
            Pfc=Pmax;
            Pbatt=Preq-Pfc;
        elseif Preq > Pmin  %removed 1.2 * on 4/2/08
            Pfc = Preq;  %possibility of charging battery
here based on battery energy used
            Pbatt = 0;
        else
            Pfc= 0;
            Pbatt= Preq;
        end
    elseif Preq > Pregen
        Pbatt = Preq;
    else
        Pbatt = Pregen;
        Pbrake = Preq-Pregen;
    end
end


%SOC Biasing
b1 = 2*(SOC - Trgt) / range;
if b1 > 0
    bias = sqrt(b1);
else
    bias = -sqrt(abs(b1));
end

if Preq > 0
    if Run == 1
        if bias > 0
            if Pfc - bias*Pfc > Pmin
                Pbatt = bias * Pfc + Pbatt;
                Pfc = Pfc - bias * Pfc;
            else
                Pbatt = Pfc-Pmin + Pbatt;
```

```
                Pfc = Pmin;
            end
        else  %Pfc automatically above Pmin based on above
            if Pfc - bias*Pfc < Pmax
                Pbatt = Pbatt + bias*Pfc;
                Pfc = Pfc - bias * Pfc;
            else
                Pbatt = Pbatt + Pfc-Pmax;
                Pfc = Pmax;
            end
        end

    elseif Run == 0
        if bias > 0
            if Pfc - bias*Pfc > Pmin
                Pbatt = bias * Pfc + Pbatt;
                Pfc = Pfc - bias * Pfc;
            else
                Pbatt = Pfc + Pbatt;
                Pfc = 0;
            end
        else  %Pfc automatically Pmin or greater from above
OR it is zero and using full battery.
            if Pfc - bias*Pfc < Pmax
                Pbatt = Pbatt + bias*Pfc;
                Pfc = Pfc - bias * Pfc;
            else
                Pbatt = Pbatt + Pfc-Pmax;
                Pfc = Pmax;
            end
        end
    end
end



if Pfc > 0
    NewRun = 1;
end

Output = [Pfc,Pbatt,Pbrake,NewRun,Pmax,Pmin,bias];


end
```

Battery Model

```
function[Output]=BattModel(Pbatt,SOC,NomV,OCV100,b,step)

%Add- calculate OCV of battery based on SOC

dR=0.25; %discharge resistance
cR=0.25; %charge resistance

if Pbatt > 0
    Propel = Pbatt;
    Regen = 0;
else
    Regen = Pbatt;
    Propel = 0;
end

%Open Circuit Voltage calculation
OCV = NomV + (OCV100-NomV)*SOC;

%Current calculation
propelcurrent = (OCV - sqrt(OCV^2-4*dR*Propel))/(2*dR);
regencurrent = (OCV - sqrt(OCV^2-4*cR*Regen))/(2*cR);

%Power loss calculation
Ploss = propelcurrent.^2*dR + regencurrent.^2*cR; %W

%Internal power calculation
Pbattint = Propel + Regen + Ploss; %W

%New SOC
SOCnew = SOC - Pbattint*step/b;

%New OCV
OCV2 = NomV + (OCV100-NomV)*SOCnew;

%Voltage @ time step
V = OCV2 - propelcurrent*dR - regencurrent*cR; %V

Output=[V,Pbattint,SOCnew,OCV2];
```

Engine-Generator Model

```
function[Output]=EGENeta(Pout)

%Engine constants
Disp = 1.4;  %Engine displacement in L
Etherm = 0.39; %Indicated thermo efficiency
fmep = 170; %[kPa]
geta = 0.92;  %generator efficiency


rpm_base = 1300; %rpm
omega_base = rpm_base*2*pi/60; %[rad/s]
torque_base_peak = 120; %[N-m]
torque_rising_rate = .04; %N-m/rpm
peaktorq = 175;
Power_base_peak = torque_base_peak * omega_base;

%Constant generator efficiency
Peng = Pout / geta;

if Peng > Power_base_peak

    P = Power_base_peak;
    rpm = rpm_base;
    torq = torque_base_peak;

    while P < Peng
        rpm = rpm + 1;
        w = rpm*2*pi/60;
        if torq < peaktorq
            torq = torq + torque_rising_rate;
        else
            torq = peaktorq;
        end
        P = w * torq;
    end

else
    rpm = rpm_base;
    torq = Peng / omega_base;
    P=Peng;
end

Eta=Etherm/(1+(fmep*Disp)/(4*pi*torq));

Output=[Eta,rpm,torq,Peng,P];
```

Fuel Cell Model

```
function[eff]=FCeff(Pout,Pmax)

Load=Pout/Pmax*100;  % percent load

boost=0.96; %boost converter efficiency

y=[0,.55,.52,.35];
x=[0,10,40,100];

eff=interp1(x,y,Load)*boost;
```