ENERGY LOSSES FOR PROPELLING AND BRAKING CONDITIONS OF AN ELECTRIC VEHICLE

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Abstract

The market segment of hybrid-electric and full function electric vehicles is growing within the automotive transportation sector. While many papers exist concerning fuel economy or fuel consumption and the limitations of conventional powertrains, little published work is available for vehicles which use grid electricity as an energy source for propulsion. Generally, the emphasis is put solely on the average drive cycle efficiency for the vehicle with very little thought given to propelling and braking powertrain losses for individual components. The modeling section of this paper will take basic energy loss equations for vehicle speed and acceleration, along with component efficiency information to predict the grid energy consumption in AC Wh/km for a given drive cycle.

This paper explains how to calculate the forces experienced by a vehicle while completing a drive cycle in three different ways: using vehicle characteristics, United States Environmental Protection Agency's (EPA) Dynamometer 'target' coefficients, and an adaptation of the Sovran parameters. Once the vehicle forces are determined, power and energy demands at the wheels are determined. The vehicle power demands are split into propelling, braking, and idle to aide in the understanding of what it takes to move a vehicle and to identify possible areas for improvement. Then, using component efficiency data for various parameters of interest, the energy consumption of the vehicle as a pure EV is supplied in both DC (at the battery terminals) and AC (from the electric grid) Wh/km. The energy that flows into and out of each component while the vehicle is driving along with the losses at each step along the way of the energy path are detailed and explained. The final goal is to make the results of the model match the vehicle for any driving schedule. Validation work is performed in order to take the model estimates for efficiencies and correlate them against real world data. By using the Virginia Tech Range Extended Crossover (VT_{REX}) and collecting data from testing, the parameters that the model is based on will be correlated with real world test data. The paper presents a propelling, braking, and net energy weighted drive cycle averaged efficiency that can be used to calculate the losses for a given cycle. In understanding the losses at each component, not just the individual efficiency, areas for future vehicle improvement can be identified to reduce petroleum energy use and greenhouse gases. The electric range of the vehicle factors heavily into the Utility Weighted fuel economy of a plug-in hybrid electric vehicle, which will also be addressed.

Acknowledgments

The contributions of the research, modeling, and results from the HEVT design team are gratefully acknowledged. I would like to thank General Motors, the U.S. Department of Energy, Argonne National Labs, and the rest of the sponsors of the EcoCAR competition. Finally I would like to thank HEVT Faculty Advisor Dr. Doug Nelson, and all of the team members from the 2009-2011 Hybrid Electric Vehicle Team.

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Equations

Abbreviations

AC:	Alternating Current (Grid)
ANL:	Argonne National Labs
AVTC:	Advanced Vehicle Technology Competition
B20:	20 % Bio-Diesel 80 % Diesel fuel
BAS:	Belted Alternator Starter
BEV:	Battery Electric Vehicle
CAFE:	Corporate Average Fuel Economy
CD:	Charge Depleting
CS:	Charge Sustaining
CV:	Constant Velocity (referring to an axle)
DC:	Direct Current (HV Bus)
DOE:	United States Department of Energy
E85:	85 % ethanol (corn) 15 % gasoline
E&EC:	Emissions and Energy Consumption
EREV:	Extended Range Electric Vehicle
EV:	Electric Vehicle
EPA:	U.S. Environmental Protection Agency
FTP:	Federal Test Procedure
GHG:	Greenhouse Gas
GM:	General Motors
HEVT:	Hybrid Electric Vehicle Team of Virginia Tech
HV:	High Voltage
$LiFePO_4$:	Lithium Iron Phosphate
NiMH:	Nickel Metal Hydride
HWFET:	Highway Fuel Economy Test (Driving Schedule)
NVFEL:	National Vehicle and Fuel Emissions Laboratory
PEU:	Petroleum Energy Use
PHEV:	Plug-in Hybrid Electric Vehicle
PSAT:	Powertrain Systems Analysis Toolkit
RESS:	Rechargeable Energy Storage Subsystem
RTM:	Rear Traction Motor
SOC:	State of Charge
UDDS:	Urban Dynamometer Driving Schedule
UF:	Utility Factor
US06:	Supplemental Federal Test Procedure (Driving Schedule)
VTS:	Vehicle Technical Specifications
VT_{REX}:	Virginia Tech Range Extended Crossover
WTW:	Well-to-Wheels
505:	First 505 seconds of the UDDS

Nomenclature

F_{tr}	Tractive Force required at the wheels	[kN]
$F_{rolling}$	Force required to overcome rolling resistance	[kN]
F_{aero}	Force required to overcome aerodynamic drag	[kN]
$F_{inertia}$	Force required to overcome inertial drag	[kN]
F_{grade}	Force required to overcome an inclination	[kN]
c_{rr_0}	Static coefficient of rolling resistance	[-]
c_{rr_1}	Moving coefficient of rolling resistance	[-]
m	Vehicle test mass	kg
g	Gravity	$\frac{\mathrm{m}}{\mathrm{s}^2}$
V	Velocity	$\frac{\mathrm{m}}{\mathrm{s}}$
ρ	Density of air	$\frac{\mathrm{kg}}{\mathrm{m}^3}$
C_D	Coefficient of Drag	[-]
A_f	Frontal Area	m^2
M_i	Inertia mass factor	[-]
$\frac{dV}{dt}$	Drive cycle acceleration	$\frac{\mathrm{m}}{\mathrm{s}^2}$
θ	Degree of inclination	[deg]
A	Target EPA dyno coefficient	lbs
B	Target EPA dyno coefficient	$\frac{\mathrm{lbs}}{\mathrm{mph}}$
C	Target EPA dyno coefficient	$\frac{\mathrm{lbs}}{\mathrm{mph}^2}$
P	Power	kW
S	Drive cycle Distance	km
α	Coefficient for propelling energy to rolling resistance	$\frac{\mathrm{m}}{\mathrm{s}^2}$
β	Coefficient for propelling energy to aerodynamic drag	$\frac{\mathrm{kg}}{\mathrm{ms}^2}$
γ	Coefficient for propelling energy to inertia	$\frac{\mathrm{m}}{\mathrm{s}^2}$
λ	Coefficient for propelling energy to grade	$\frac{\mathrm{m}}{\mathrm{s}^2}$

Δ	Coefficient for propelling energy to rolling resistance proportional to Velocity	$\frac{m^2}{s^3}$
α'	Coefficient for braking energy to rolling resistance	$\frac{m}{s^2}$
β'	Coefficient for braking energy to aerodynamic drag	$\frac{kg}{ms^2}$
γ'	Coefficient for braking energy to inertia	$\frac{m}{s^2}$
λ'	Coefficient for braking energy to grade	$\frac{m}{s^2}$
Δ'	Coefficient for braking energy to rolling resistance proportional to Velocity	$\frac{m^2}{s^3}$
E_{tr}^{+}	Positive tractive energy required for a drive cycle	MJ
E_{tr}^{-}	Negative tractive energy required for a drive cycle	MJ
t	Drive cycle time	s
ζ	Fraction of negative tractive energy allowed to be recaptured	[-]
L	Energy losses in powertrain components	[Wh]
η_{drive}	Energy weighted driveline efficiency	[-]
η_{motor}	Energy weighted motor efficiency	[-]
η_{batt}	Energy weighted battery eficiency	[-]
$m_{battery}$	Mass of Battery Modules	kg
E_{CAP}	Energy capacity of RESS	kWh
K_c	Copper Losses	[-]
K_i	Iron Losses	[-]
K_w	Windage Losses	[-]
C	Constant Losses	[-]
V_{oc}	Open Circuit Voltage of the RESS	[Volts]
η_{pr}	Drive cycle average energy weighted propel efficiency	[-]
η_{br}	Drive cycle average energy weighted braking efficiency	[-]
η_{net}	Drive cycle average energy weighted cycle efficiency	[-]

1. Introduction

1.1 The need for new energy

America consumes oil at an astounding rate, and one day soon, that will no longer be a viable option. Oil comes from fossil fuels which are a non-renewable resource that is primarily located outside US borders. Worse still, in a nation concerned with terrorism, the U.S. imports 1 in every 5 barrels of oil from countries that the U.S. State Department labels as "dangerous or unstable" [1]. In a manner similar to President Kennedy's quest for the U.S. to reach the moon first, President Obama has challenged the automotive industry and consumers alike to have 1 million plug-in hybrid electric vehicles on the road by 2015 [2]. This challenge transcends the automotive industry, pushing battery technology and increasing the demand for electricity on the electric grid. There is some concern that electric vehicles, which would raise household utilities bills by about 33%, could blackout a neighborhood during peak hours. However, this problem is only relevant if everyone on a block owns a plug-in and the grid has not been updated to account for the increased load [3] if charging occurs during peak usage times.

With electrified vehicle powertrains comes the ability to remove some of the dependence on foreign oil. The average American drives less than 40 miles a day on average, so a vehicle with a 40 mile electric vehicle (EV) range will allow the average American to complete their commute without using any gas [4]. A typical gasoline engine may have a peak efficiency of 35%, while an electric motor may have a peak efficiency of 95%, so electrified vehicles can use the energy stored on board the vehicle much more efficiently. Vehicle electrification also affords the vehicle the chance to recapture some energy, through regenerative braking, that would otherwise be lost to heat in friction brakes. Currently, the electric grid in North America produces about 50% of electricity from coal, but as more renewable and alternative energy sources come online, the greenhouse gas (GHG) impact of an electric vehicle will reduce the carbon footprint created by the transportation sector even more. The adoption of newer technology that does not use fossil fuels but includes clean energy sources such as wind, solar, geothermal, wave, and hydroelectric power, are viable options for the electricity generation. In order to further reduce petroleum energy use at the vehicle level bio-diesel (B20) and ethanol (E85) can be used as substitutes for 100% petroleum based liquid fuels. Vehicles that can take advantage of electricity and lower petroleum content fuels are the next step towards a transportation industry that is focused on higher fuel economy, lower petroleum energy use (PEU), and lower GHG use.

1.2 EcoCAR: the NeXt Challenge

The Hybrid Electric Vehicle Team (HEVT) of Virginia Tech has designed and built a range extended crossover vehicle to compete in EcoCAR: the NeXt Challenge. EcoCAR is a three year advanced vehicle technology competition (AVTC) [5-8] with headline sponsors General Motors (GM) and the United States Department of Energy (DOE). The VT_{REX}, as the car is referred to by the team, is an extended range electric vehicle (EREV) with an all-electric range of greater than 80 km. A 125 kW peak electric motor and a single speed gear reduction transmission is used to transfer the electric motor torque to the rear wheels of the vehicle. During EV operation, the vehicle maintains functionality of safety and consumer features such as: power assist friction brakes, a DC/DC source to supply 12 V accessory loads, electric air conditioning compressor and electric power steering. These features are required to be electrically driven instead of mechanically driver due to the significant time of operation when the engine is not running as in a conventional vehicle. Once the battery energy is depleted from the rechargeable energy storage subsystem (RESS), the vehicle moves from charge depleting (CD) into charge sustaining (CS) operation. The range extender is a 2.4 L FlexFuel engine, meaning that the engine can run on ethanol content ranging from 0 to 85 % and still maintain closed loop operation. The engine which a 4-speed automatic transmission on the front axle of the vehicle and has no mechanical path to the rear axle of the vehicle., except through the road While operating in CS, the vehicle controller selects the best operating point to meet driver demand by using a combination of the electric rear traction motor (RTM), the engine, and the belted alternator starter (BAS) motor. The mechanical and electrical energy flow paths of the VT_{REX}, can be seen in Figure 1.

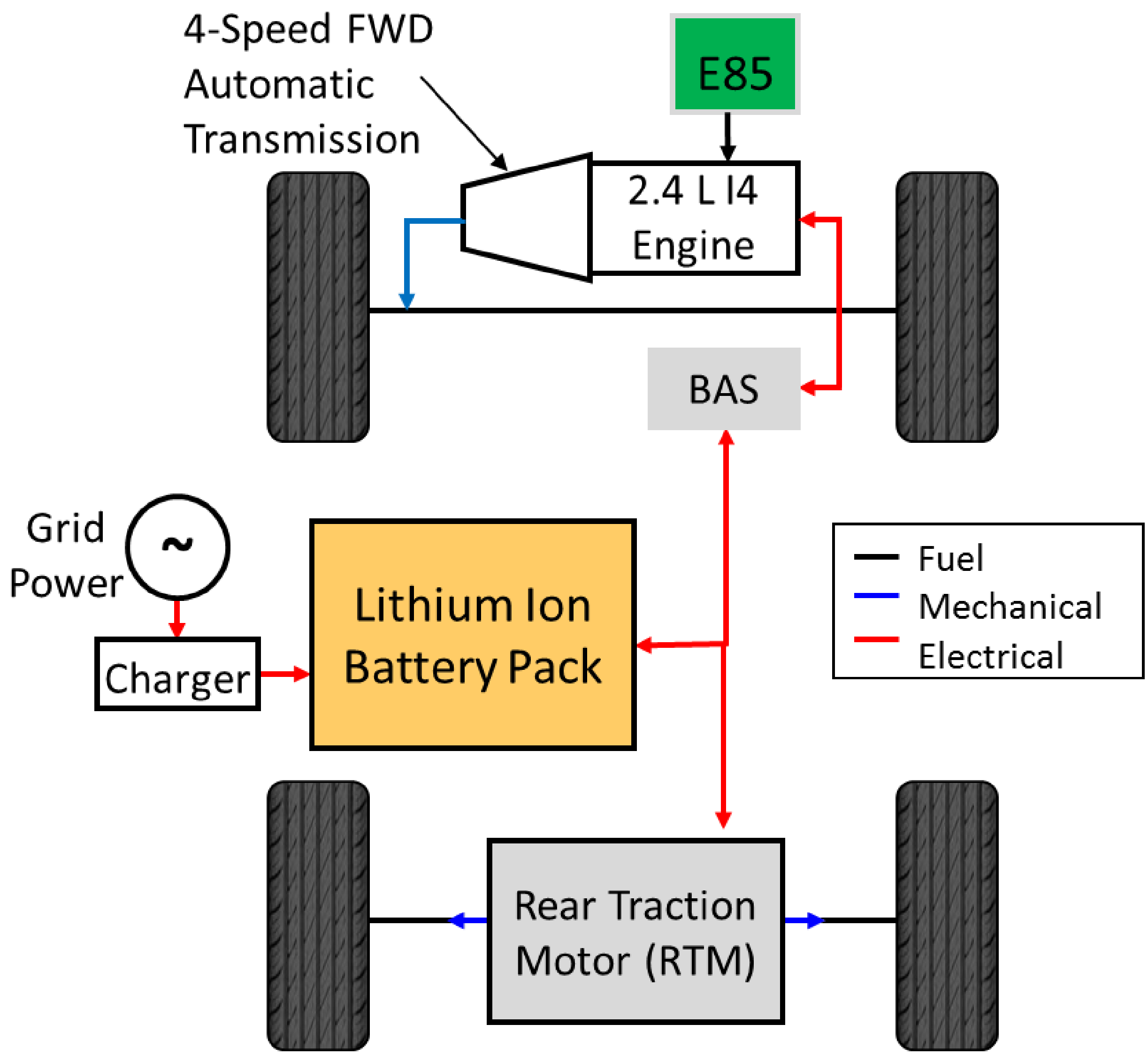

Figure 1: VT_{REX} Energy Flow Path

In year 1 of the EcoCAR challenge, the team was tasked with selecting an overall hybrid architecture, team goals, and vehicle technical specifications (VTS) – these goals are reflected in the energy flow path shown in Figure 1. While the vehicle architecture has not changed over the three years of competition, many of the components have. HEVT chose to design a vehicle that had a significant electric only range, which was determined by the team to be more than 35 miles as a pure EV. Also, the team chose to reduce petroleum energy use by relying on grid electricity and E85 Ethanol as energy sources. The petroleum energy content of the fuel is based on the well-to-pump and pump-to-wheels numbers developed by Argonne National Labs (ANL) Greet model [9]. The target is to reduce the PEU on a well-to-wheel (WTW) energy cycle by over 80 %. Figure 2 shows a plot of petroleum energy content per kWh of fuel against the petroleum energy consumption for the VT_{REX}. The five bar lines represent the five candidate fuels available to be used in the EcoCAR challenge. The black dot on the gasoline bar represents the stock vehicle, while the 2 blue points represent the 2 distinct operating modes of the VT_{REX}: CS and CD. The utility factor (UF), weighted point on the graph is an SAE J1711 weighting of the vehicle's equivalent fuel economy when considering a fleet average energy use of both electricity and E85 ethanol [4]. This is important as there are several different types of UF weighting, individual or fleet based averages.

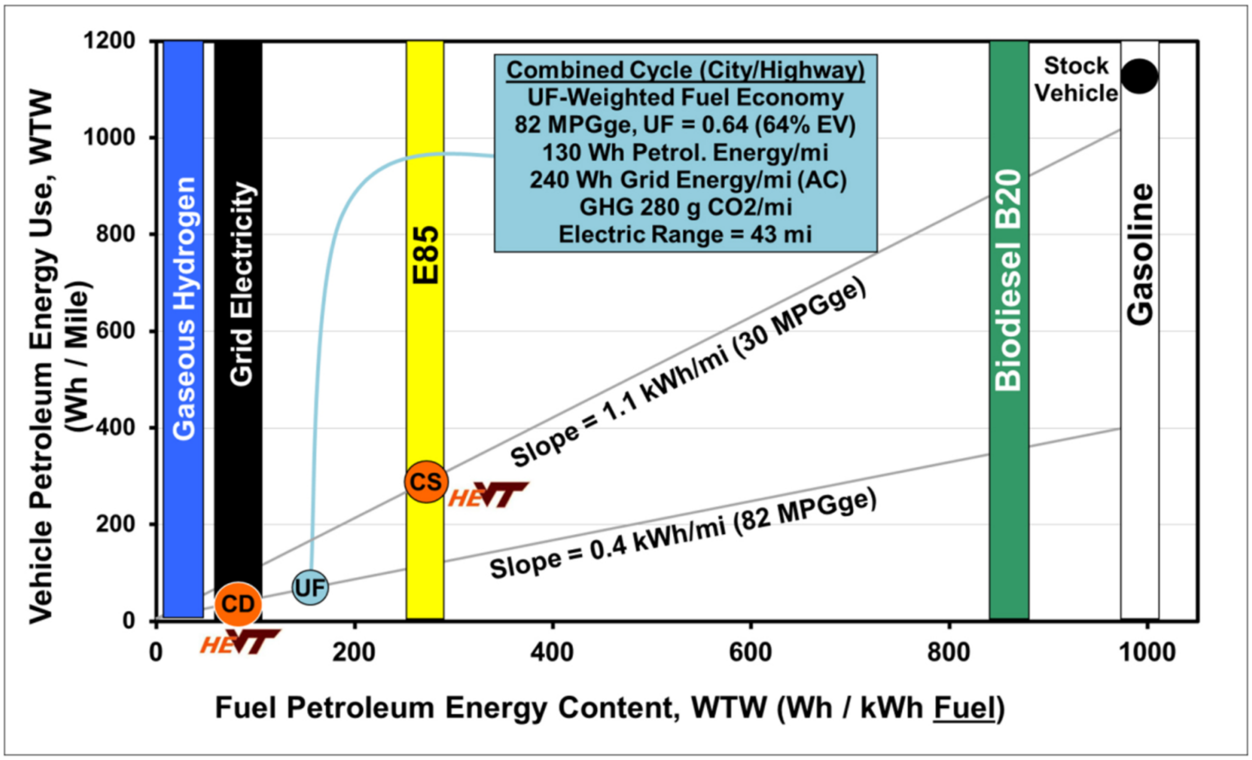

Figure 2: WTW PEU plot for EcoCAR fuels, with vehicle efficiency lines.

Hydrogen, while very attractive as a low petroleum content fuel, would have led to packaging large storage tanks and added vehicle mass; therefore, without a current fueling infrastructure present in North America, hydrogen was not selected. HEVT decided to use stored on-board grid energy to reduce petroleum energy used. The stored grid energy will not be able to propel the vehicle for the full range requirement of EcoCAR, 200 mi, so E85 was selected to further reduce the consumption of petroleum energy and provide a range extension feature.

Figure 3 is a representation of total GHG emissions. One way to lower the total emissions associated with the vehicle is to select a fuel that has low vehicle emissions at the tailpipe, such as electricity (zero). HEVT decided to use stored on-board grid energy in the form of a plug-in hybrid to utilize the low vehicle GHG emissions of electricity. This decision was based primarily on the ability to meet the large electric range goal set forth by HEVT, as well as the knowledge that the energy from electricity can be used much more efficiently on the vehicle than energy from a typical liquid fuel like E85. Even though the upstream GHG emissions associated with electricity are the highest of the candidate fuels, the high efficiency of an electric vehicle helps to reduce the overall WTW impact. The amount of GHG reduction achieved is about 30% but this number will only increase as the electric grid becomes more renewable in the future. Just as with PEU, HEVT looks forward to being able to claim the use of Cellulosic E85 particularly for GHG reduction purposes.

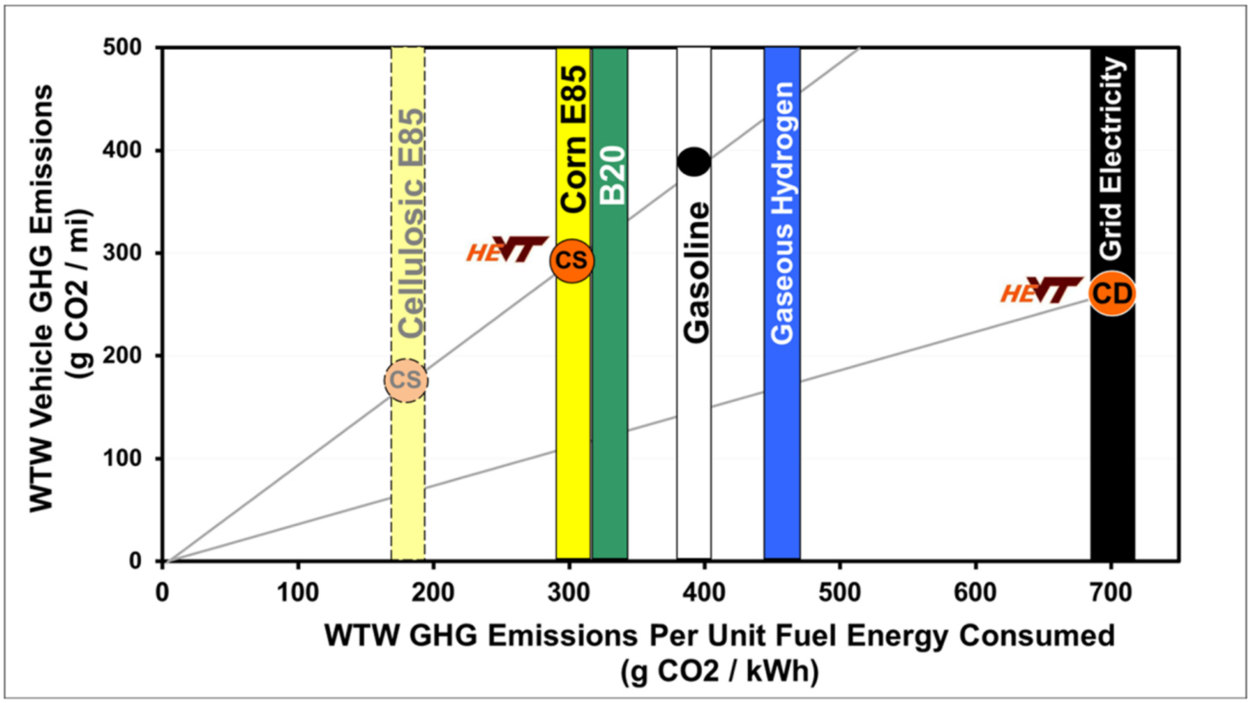

Figure 3: WTW GHG emissions plot for EcoCAR fuels, with vehicle efficiency lines.

1.3 E-REV, PHEVs, and EVs

In the Late 1990's Ford and General Motors produced a small number of pure battery electric vehicles (BEV), the Ranger and EV1, respectively. The generation 1 EV1, was released with Lead Acid Batteries, which were upgraded later to Nickel-Metal Hydride (NiMH) battery packs in the generation 2 vehicle. Figure 4 shows an image of the EV1. The drawback of a pure electric vehicle is the limited range available with the then-current battery technology. While most current production hybrid vehicles like the Toyota Prius utilize a power battery pack to recapture some energy and supply it back into the powertrain as electric assist, a BEV or EREV battery pack must have a large energy capacity to meet customer range requirements. Newer battery chemistries using Lithium Ion technologies have been adapted by several companies in the last few years with promise of providing reliable, safe batteries suitable for mass production. Nissan is now releasing a new model called the Leaf which is a pure EV claiming to provide 100 miles range, while GM has decided to go the path of an Extended Range Electric Vehicle (E-REV) with its new offering, the Chevy Volt, with other automotive companies producing concepts.

Figure 4: General Motors EV1

An EREV is a specific type of a Plug-in Hybrid Electric Vehicle (PHEV) in that the vehicle can provide full performance in both CD and CS modes for an extended range. Current aftermarket PHEV conversions, like the Toyota Prius vehicles with A123 Hymotion batteries, do not qualify as an EREV because the electric energy is blended in (no true electric only range) due to the limitations of the powertrain requiring the engine to spin above some power, torque, or speed demand to meet the driver request [10]. The VT_{REX} uses Lithium Iron Phosphate ($LiFePO_4$) prismatic cells to make up a 20 kWh RESS, using modules and controllers from A123 Systems. An EREV by definition can meet full performance requirements as a pure EV which is not the case with a PHEV.

1.4 Objectives

The overall objective of this paper is to define an approach to predict the electric consumption of an electric only powertrain. The work takes the tractive energy requirements at the wheels and splits the energy required into propelling, braking, idle, and charge cases. By understanding what amount of energy is used in propelling and braking at the wheels and tracing the losses through the powertrain to the electrical requirements at the RESS, the net energy flow can be calculated to complete a given drive cycle. The importance of this work is that it gives insight into vehicle development parameters and allows the end user to directly see the impact of changing vehicle design parameters. There are several vehicle parameters which when changed result in a different EV range, which impacts the utility factor weighted fuel economy for a PHEV/EREV. The changes can also impact design criteria such as motor sizing for peak power or torque, along with required battery capacity to meet the design goals. Table 1 shows the parameters of interest and the variables that the model uses to ensure that the design metrics established are met. Based on the vehicle specific design parameters and the drive cycle a propelling and braking efficiency can be calculated. This efficiency translates how much energy is needed from the RESS to meet the tractive propelling energy requirements, and how much of the energy at the wheels is stored in the RESS during braking. A total net powertrain and braking efficiency term is presented as well, that takes into account the net energy required to complete a drive cycle. Vehicle range (km) and electrical energy consumption (Wh/km) will be reported based on the energy that is at the terminals of the RESS and also the energy required from the electric grid to store the energy in the RESS to meet the range requirements. The current model is developed and validated against the $VT_{REX,}$ however the model was developed with the intention of future students involved in hybrid electric vehicle design problems to be able to input their vehicle glider and powertrain requirements into the model and gain insight into the vehicle energy consumption. Note that the powertrain specific efficiencies will change based on the torque and speed loading required which will change for different vehicle platforms.

Table 1: Vehicle Properties and Design Specifications

Design Parameters
Test Mass (kg)
Coefficient of Rolling Resistance (C_{rr})
Coefficient of Drag (C_D)
Battery Efficiency for $\pm$ current (A)
Motor Efficiency for $\pm$ torque (Nm)
Driveline Efficiency for $\pm$ torque (Nm)
Effective Regenerative Recapture
Battery Charging Efficiency (%)
Accessory Load (W)
Vehicle Gearing

Design Specifications
Battery Capacity (kWh)
Motor Peak Power (kW)
Motor Peak Torque (Nm)
EV Range (km)
Utility Factor Weighting
Electric Energy Consumption (Wh/km)

This paper explains how to calculate the forces experienced by a vehicle while completing a drive cycle in three different ways: using vehicle characteristics, United States Environmental Protection Agency's (EPA) Dynamometer 'target' coefficients, and an adaptation of the Sovran parameters. Once the vehicle forces are determined, power and energy demands at the wheels are determined. The vehicle power demands are split into propelling, braking, and idle to aide in the understanding of what it takes to move a vehicle and to identify possible areas for improvement. The original model design parameters are based on supplier information, which in general listed peak efficiencies not drive cycle average energy weighted efficiencies. The idea of a drive cycle average energy weighted efficiency is that using a single number, say propelling efficiency, the end user can directly and correctly determine the energy required from the RESS, just by knowing the energy at the wheels for the propelling case. In order for that efficiency term to be correct all of the losses in the powertrain have to be accounted for correctly and in a logical way. Data was collected on the vehicle during testing, which was used for model validation. The model predicts the estimated range of the VT_{REX} as well as the energy used at the terminals of the RESS, DC Wh/km, and energy required from the electrical gird, AC WH/km. By using the VT_{REX} as shown in Figure 5 along with the model the goal is to identify possible areas of improvement for future researchers to focus on. In understanding the powertrain losses the model provides a way to reduce petroleum consumption, GHG emissions, and improve the utility factor weighted fuel economy in a virtual design case to be applied in future competition build vehicles.

Figure 5: VT$_{REX}$ at General Motors Desert Proving Grounds: Yuma, AZ

A literature review is available in Section 2 of this paper which gives background information on tracking energy flows in vehicle powertrains. The literature review also gives a technical introduction into hybrid vehicle types and testing procedures for valid real world results. Section 3 outlines the model developed for the preliminary prediction of the VT$_{REX}$ electric only range. The preliminary model is based on kinematic equations and several assumptions which have been updated and validated using the test results from EPA dynamometer testing as shown in Section 4. Section 5 will discuss possible applications of this model as a simple design tool to be used by future team members of HEVT. Section 6 gives overall conclusions about what should be gathered from this model and the limitations of the results presented.

2. Literature Review

The purpose of this literature review is to establish the ground work that has been done by other authors on predicting energy consumption for vehicle platforms. Emphasis will be given on papers that explain the tractive effort at the wheels, or minimum vehicle propulsion required for a given vehicle architecture. Also of interest is how to calculate and represent losses, energy flow paths, and component efficiencies so that the energy is correctly accounted for at each step along the powertrain in addition to the vehicle energy consumption number being correct. While most of the papers below focus on a conventional powertrain with a liquid fueled engine, the practices can be applied to an electric vehicle, which is the purpose of this thesis.

2.1 Sovran

2.1.1 Formulae for the Tractive-Energy Requirements of Vehicles Driving the EPA Schedules [11].

In 1981 Sovran published a work at SAE World Congress that established a methodology for determining the tractive effort required at the wheels for the US EPA: UDDS and HWFET drive cycles [12]. Sovran explains in detail what portion of the energy goes to overcoming road load in rolling resistance and aerodynamic drag. Road load is only a portion of the force experienced by the vehicle, the total tractive energy requirement also includes inertia. Sovran establishes a detailed set of vehicle specific parameters for rolling resistance, aerodynamic drag, and inertia (kinetic) energy requirements for each drive schedule. Sovran takes care to separate the energy required for propelling and braking into two separate categories. Attention is taken throughout the work to ensure that the energy at the wheels is explained correctly.

The work by Sovran is a first in a series of papers explaining the forces experienced by a vehicle. Sovran established 5 conclusions from his work in 1981 which still hold true today even with the current generation of hybridization in automobiles. The conclusions are functions for specific energy of rolling resistance, aerodynamic drag, and kinetic energy that still capture the tractive effort at the wheels correctly. The work within this thesis will consider the second coefficient of rolling resistance, that is proportional to velocity as a separate term, when the data is available. Also, outside of the scope of Sovran's work with the EPA drive schedules is the importance in understanding the impact of elevation change during a drive cycle even if the net change is zero. A net zero elevation change happens to vehicles every day when they return to the same home, but yet have gone up and down several inclines. Grade will also be included within this thesis as it does impact the tractive effort required at the wheels for real world driving. By recording elevation change, the model can more accurately predict energy consumption and range.

2.1.2 A Contribution to Understanding Automotive Fuel Economy and Its Limits

Sovran took the 1981 paper one step further and looked at overall conventional powertrain components and set not only tractive energy requirements but predictions for fuel economy in his 2003 SAE Transactions paper [13]. Sovran used the same specific energy weighted equations but now added another category for application. Propelling and braking were initially considered, but now since the end goal is fuel economy, not just energy at the wheels, idle time is also considered. The paper focuses on Corporate Average Fuel Economy (CAFE) and how to predict vehicle fuel economy in the initial design stages using a set of energy weighted component efficiencies based on vehicle powertrain specific data. The majority of the paper goes through in detail again everything published in the 1981 paper, and a comment on the work performed by the National Research Council in 2001. What Sovran states is that to accurately predict vehicle fuel consumption, a drive cycle energy averaged number must be quoted against the EPA cycles in order for it to be relevant. That while improvements in efficiency for one particular component can be made, that does not necessarily translate to a decrease in fuel consumption if that operation point is never used during the drive cycle.

One important concept that this paper establishes well is the idea of an energy weighted drive cycle averaged efficiency. This concept is important because the drive cycle energy weighted average idea allows for a simple and direct calculation of what amount of energy going into and out of a component. The energy flow information leads to the calculation of efficiencies for the propelling and braking cases. In a simple 1 Hz model of a vehicle, a summation of the efficiency points over all of the propel points for a drive schedule is performed, the efficiency number will not be the same as an energy weighted drive cycle average efficiency value. This concept is important and applied in the modeling section of this thesis as it leads to true estimates of efficiencies and losses at each component. Sovran mainly focuses on conventional vehicle powertrain (gasoline-fueled engines) with a small section of hybridization. But rather than a good set of equations specific to determining the energy consumption of the electric portion of the vehicle powertrain it is more of a summary of why hybrid powertrains can improve fuel economy. The goal of the Sovran paper is the same as this thesis: explain energy consumption of the vehicle in a way that allows for complete understanding of the powertrain losses and powertrain efficiencies in a way that allows for discussion. Discussion leading to ways to improve vehicle designs with predictive data, that is well understood with very little limitations and qualifying statements is the end result of applying Sovran's design concept.

2.1.3 Quantifying the Potential Impacts of Regenerative Braking on a Vehicle's Tractive-Fuel Consumption for the U.S., European, and Japanese Driving Schedules

The 2006 Sovran paper gives an increased emphasis on how regenerative braking can decrease fuel consumption [14]. The major limitation of this work is how Sovran accounts for the decrease in fuel consumption. The paper uses a simple efficiency term, that is a multiplier of the available brake energy at the wheels. While the approach that Sovran uses to predict fuel economy is a relatively good model, this is a major shortcut. The idea is sound, some amount of energy available at the wheels is stored in a hybrid battery pack and used later to offset fuel use by supplying electrical loads during idle with the engine off for example. The major limitation is that Sovran sets everything up so clearly for easy understanding of what happens at each step along the way for the propelling case, and now there is just this overarching term that sweeps all the losses under the rug for the braking case. While not considered in this thesis, Sovran also demonstrates how the specific energy parameters can be applied to more than just the EPA drive cycles, as Sovran includes insight into some European and Japanese drive schedules as well.

Rather than using a brake energy multiplier to account for a decrease in fuel consumption, this work will account for the energy flow in the braking direction just as in the propelling direction. During the course of this study in general the drive cycle energy weighted efficiency terms are different in most cases for propelling and braking, as the loads experienced are not the same for each case. This difference means that for tracking and understanding the losses and energy flow path of an electric vehicle; just having a single electric motor efficiency energy weighted term is not enough, there must be an efficiency for braking and propelling. The work also found this a propelling and braking efficiency to be required for the transmission and RESS.

2.2 Hochgraf: What if the Prius Wasn't a Hybrid? What if the Corolla Were? An Analysis Based on Vehicle Limited Fuel Consumption and Powertrain and Braking Efficiency

Hochgraf and Douba present an interesting paper on vehicle limited fuel consumption and powertrain and braking efficiency [15]. Hochgraf takes into account powertrain and non-powertrain related improvements made to vehicles and the impacts that has on the vehicle powertrain and braking efficiency values. The powertrain and braking efficiency is defined as the vehicle limited fuel consumption over the vehicle fuel consumption, with the vehicle limited fuel consumption being what is required at the wheels to complete a drive cycle. This concept is similar to Sovran's tractive effort at the wheels analysis, explained previously. Hochgraf rather than using the vehicle specific parameters uses the coast down data provided by EPA for their dynamometer target coefficients (A, B, and C). The approach used by Hochgraf assumes that all inertial energy for accelerating the vehicle is equal to the braking energy recaptured by regenerative braking at 100 % efficiency and thus only considers road load power.

This concept of knowing the exact minimum fuel consumption and the increased fuel consumption due to powertrain losses provides a unique insight into vehicle development. The study considers hundreds of 2009 production model vehicles, and thus provides an overall summary of the results. While the idea of an overall powertrain and braking efficiency is used in this study, this thesis will break them down into two separate efficiency values additionally. The purpose behind this is so that the end user can directly see how much of the energy available for regenerative braking recapture actually made it back into the RESS.

2.3 Yanni: Impact and Sensitivity of Vehicle Design Parameters on Fuel Economy Estimates

Yanni has developed a set of modeling equations that allow the end user the ability to predict energy consumption without having to use a time based, second by second, modeling system [16]. Yanni references the program known as Powertrain Systems Analysis Toolkit (PSAT), which has been replaced by Autonomie as useful for final vehicle fuel economy models, but overwhelming in the initial design stage of concept selection [17]. However in Yanni's attempt for simplification he assumes an efficiency for the powertrain from the battery to the wheels, as 50 %. While in the initial design stage this might be appropriate it does not and will not lead to good model correlations for true design concept validation. While it may take slightly more time to step up and getting working a second by second model based on the EPA drive schedules to begin, after the initial setup, the model takes as little effort to run as the equations Yanni suggested. In using the equations described in this work, the end user receives the added benefit of seeing the direct impact of design changes on component efficiencies, component losses, and propelling and braking drive cycle average efficiencies compared to Yanni's model. Yanni makes a reasonable assumption for initial design conceptualization in that efficiencies for propelling and braking is the same. While that assumption is possible the results gathered from the study will not validate well when the vehicle goes from concept design to on road testing. The loading in torque and speed that the vehicle sees while decelerating (braking) is different from the propel case, requiring the energy weighted drive cycle averaged efficiencies to be different. One positive point in the paper is in how Yanni shows the effect of regenerative braking for a pure Battery Electric Vehicle (BEV) and the energy break down for rolling resistance, aerodynamic drag, inertia accelerating, and inertia braking.

2.4 Tate: The Electrification of the Automobile: From Conventional Hybrid, to Plug-in Hybrids, to Extended-Range Electric Vehicles

The purpose of Tate's paper is to push readers to accept EREVs as a viable transportation option that is practical unlike past BEV vehicles [18]. The paper references two GM products: The Saturn Vue Greenline PHEV, which never made it to production, and the Chevrolet Volt, which is just now ramping up production in select states across the USA. Tate set the stage for the overwhelming amount of petroleum energy that the USA will use by 2030, 118 million barrels annually. GM, through the production of PHEVs, EREVs, and BEVs over the next few decades hopes that the ecological impact of the automobile will be very small by 2030, due to reduction of petroleum energy use on board and increasing electrification of vehicle powertrains. A PHEV according to SAE is, "A hybrid vehicle with the ability to store and use off-board electrical energy in the RESS [19]." An EREV meets the classification listed for a PHEV, but with the added benefit of full performance as an electric vehicle and an extended range requirement. The extended range portion is hard to define, but is generally understood as enough range, power, and torque to meet the EPA drive cycles for federal certification testing as a pure EV. Tate quantifies estimates of fuel savings for a EREV as well as air pollution prevention based on a Regional Travel Survey. The last conclusion of the work, which resonates the most, is that according to Tate, "In the event of a petroleum disruption, an EREV could support uncompromised vehicle operation for the majority of drivers." This means that even with high liquid fuel prices or shortages, a EREV type vehicle would still allow the majority of Americans to go about their lives in a similar fashion to driving a liquid fueled vehicle.

2.5 Duoba: Calculating Results and Performance Parameters for PHEVs

The validation work done in this thesis was done at the United States Environmental Protection Agency's (EPA) National Vehicle and Fuel Emissions Laboratory (NVFEL) in Ann Arbor, Michigan. Duboa's paper explains some of the difficulty in testing and dealing with PHEVs [20]. While the testing done by the team did not need to meet federal certification requirements, the data collected was extremely helpful in validating the model within this thesis.

Duoba explains in detail the five cycles used for testing, UDDS (city), HWFET (highway), US06 (supplemental high loads), Cold FTP (-8^{0}C UDDS), and SC03 (35^{0}C with solar load and vehicle air conditioning running). While the only tests performed at EPA are with the UDDS and HWFET, the other tests bring in more realistic fuel economy (or energy consumption) numbers that drivers would see in real world driving. The UDDS has a 505 s portion at the front, that captures the first 5 hills which is assumed to capture the cold start dynamics of an conventional internal combustion engine. The federal test procedure is to run a UDDS followed by a 505, but with PHEVs and EREVs the vehicle powertrain dynamics cannot be assumed the same due to state of charge (SOC) swings and the test has been amended to back-to-back UDDS cycles.

Test time for EREVs and PHEVs increases dramatically compared to a conventionally fueled vehicle. For instance it is not enough to run a single UDDS, determine the energy consumption for that cycle, and extrapolate an estimated range for the vehicle based on energy remaining in the RESS. The only current way that the electric only range for an EREV or BEV can be determined is to do a full charge test, in which the entire charge depleting energy is pulled out of the RESS to the point in which the vehicle would start the engine and move into CS. HEVT experienced firsthand some of the difficulties listed in the study while testing at EPA's NVFEL. EREVs are helpful from a testing standpoint, in that the vehicle is able to achieve full performance as an electric vehicle and has a pure electric only range. PHEVs are not as easy to determine when the vehicle transitions into CS from CD, as the vehicles electric powertrain cannot not always meet cycle demands because of power, torque, speed, gearing, or battery current limitations, which complicates testing.

2.6 Baglione: Vehicle System Energy Analysis Methodology and Tool for Determining Vehicle Subsystem Energy Supply and Demand

Baglione while working with Daimler Chrysler, developed a model similar in concept to this thesis, except for a conventional vehicle [21]. The goal of the work is to predict reduction in energy consumption for a drive cycle, and correlate that to minor improvements to fuel economy using test data collected from previous components. While the paper focuses on improvements primarily made to a power steering pump, the tactics are sound for design improvements of a vehicle architecture. Using the model, areas of interest for improvement are identified, researched, and then if noteworthy deemed a viable solution for improving fuel economy. The model developed uses MATLAB/SIMULINK a MathWorks tool, as the model developed within this thesis primarily uses Excel a Microsoft Office tool. The equations vary, as Baglione has access to more specific test data for vehicle components. An example is rolling resistance for tires, the equation developed here within this thesis is a simple coefficient, where the model used by Baglione takes into account several factors including tire pressure, tire load, and 5 design parameters to ensure that the data in the model matches the physical test data. Real world data is key, and is what the vehicle will be measured against, but the model developed here is trying to improve the fuel economy by improving small things, like decreasing the accessory load current draw by 4 amps. The fuel economy gain could be within the noise floor of a real world test, so it is important to have well correlated models, to prove that the areas of interest identified for decreasing energy consumption on the vehicle are worth extra insight attention from a test engineer.

2.7 Summary of Literature Review

The literature reviewed within this section is meant to give the reader of this thesis a background on the problem, solutions other authors have attempted, and a review of the technology employed in the vehicle design process. The papers written by Sovran establish the basis for a tractive effort at the wheels model, that takes simple engineering equations and allows for powerful insight into vehicle energy requirements. Hochgraf takes the idea one step farther than Sovran and attempts to determine if the improvements in fuel economy are due to powertrain improvements of vehicle 'glider' properties across vehicle platforms. Yanni, a researcher from the University of Clemson in South Carolina, developed a basic model for preliminary vehicle design goals that has merit, but lacks in substance for predicting vehicle energy consumption. Tate, a GM employee, describes the benefits of increasing the amount of electrical energy used on board vehicles, while Duoba explains the increase in certification test time required for electric vehicle powertrains. On the other end of the modeling spectrum, Baglione describes a model that uses empirical data from Chrysler in order to improve fuel economy numbers by less than 0.1 mpg at a time, by researching improvements for individual components to reduce the parasitic losses present in the automobile. The literature reviewed has given the author of this thesis the background required to develop a model suitable for predicting the energy consumption of an electric vehicle by splitting the energy into propelling, braking, and idle energy over a given drive cycle. An efficiency for each segment as well as the net energy used to complete a cycle will be given, and a range prediction made for this model.

3. Modeling EV Energy Consumption

3.1 Vehicle Force Equations

3.1.1 Equations from Vehicle Parameters

A vehicle in motion experiences a set of forces (including road load), which determines the minimum force at the wheels (known as tractive effort) required to meet a given drive trace (speed and acceleration). A drive cycle can be as simple as a constant velocity on a road, or a drive cycle mandated by the US EPA: UDDS, HWFET, or US06 [12]. Equation 1 shows that the tractive effort can be broken down into four main categories, tire rolling resistance ($F_{rolling}$), aerodynamic drag (F_{aero}), overcoming the current vehicle state of motion ($F_{inertia}$), and finally the grade or inclination that the vehicle is travelling on (F_{grade}). Figure 6 shows a physical representation of the forces as they affect the vehicle during motion. Only the forces in the x-direction are accounted for in Equation 1.

$$F_{tr} = F_{rolling} + F_{aero} + F_{inertia} + F_{grade} \qquad (1)$$

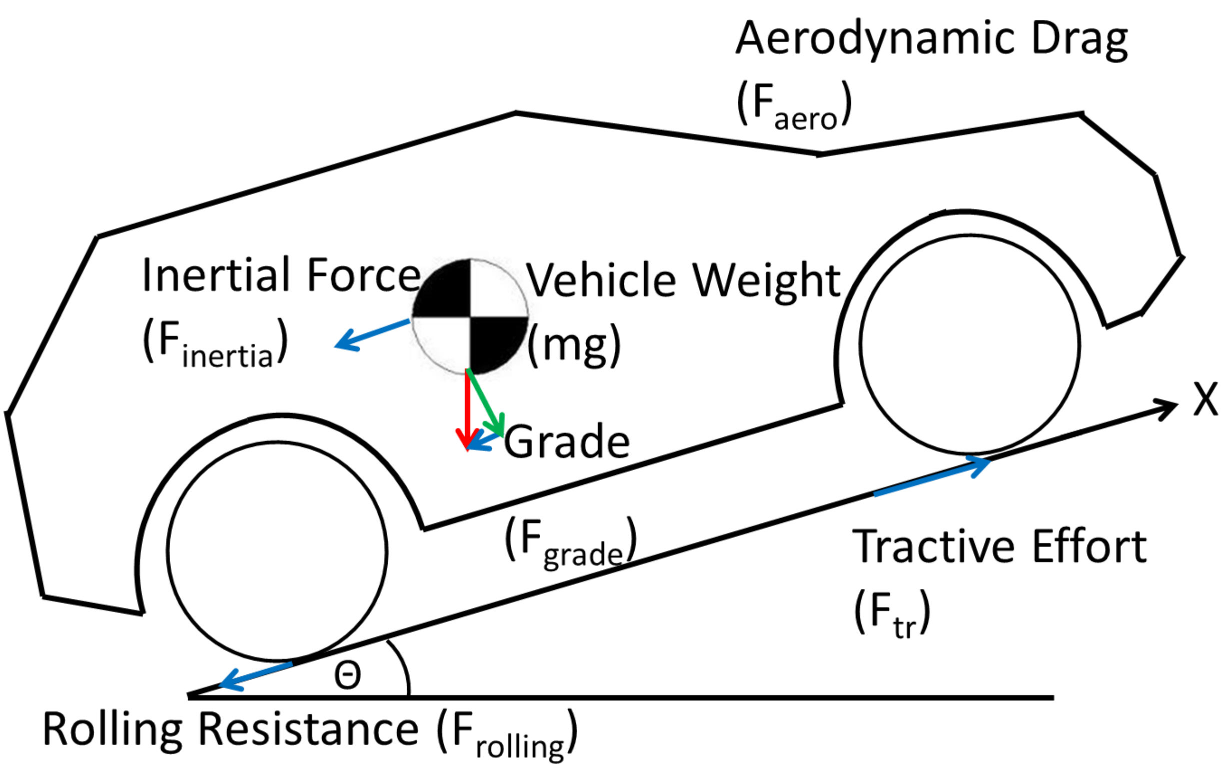

Figure 6: Road Load

Equations 2 through 4 express the different terms making up the tractive effort equation. Here, c_{rr_0} is the coefficient of rolling resistance, c_{rr_1} coefficient of rolling resistance affected by Velocity (not always included), m is vehicle mass, g is the acceleration due to gravity, ρ is the density of air, C_D is the coefficient of drag, $A_f$is the frontal area of the vehicle, V is the velocity for the drive cycle, M_i is an inertial mass factor term to account for the rotating inertia of the wheels, tires, and other rotating components, $\frac{dV}{dt}$ is the acceleration from one time step to the next for the drive cycle, and θ (related to grade) is the angle of incline. For normal inclines, the $\cos(\theta)$ term that could be included in Equation 2 is approximated as 1. The variables are summarized in Table 2 for reference as well as in the Nomenclature section.

$$F_{rolling} = c_{rr_0} mg + c_{rr_1} mgV \tag{2}$$

$$F_{aero} = \frac{1}{2} \rho C_D A_f V^2 \tag{3}$$

$$F_{inertia} = mM_i \frac{dV}{dt} \tag{4}$$

$$F_{grade} = mg\, sin(\theta) \approx mg * grade \tag{5}$$

Table 2:Vehicle Force Parameters

c_{rr_0}	Static coefficient of rolling resistance	[-]
c_{rr_1}	Moving coefficient of rolling resistance	[-]
m	Vehicle test mass	kg
g	Gravity	$\frac{\mathrm{m}}{\mathrm{s}^2}$
V	Velocity	$\frac{\mathrm{m}}{\mathrm{s}}$
ρ	Density of air	$\frac{\mathrm{kg}}{\mathrm{m}^3}$
C_D	Coefficient of Drag	[-]
A_f	Frontal Area	m^2
M_i	Inertia mass factor	[-]
$\frac{dV}{dt}$	Drive cycle acceleration	$\frac{\mathrm{m}}{\mathrm{s}^2}$
θ	Degree of inclination	[$^{\mathrm{O}}$]

The rolling resistance term is always present when the vehicle is in motion. Aerodynamic drag force increases with the square of velocity, so with higher speeds comes more drag on the vehicle. The inertia term is dependent on vehicle acceleration rate, and will sum to zero for a drive cycle that starts and ends at zero speed. Grade, while not always present, does have an impact on the energy required to complete a drive cycle, and if present, should be accounted for. More background on the forces experienced by a vehicle are given by Husain [22] and Ehsani et al. [23].

3.1.2 EPA Vehicle Dynamometer Target Coefficients

The standard drive cycles used for vehicle certification by the EPA are the UDDS, HWFET, and now US06. These drive cycles are used for the majority of the reported results in this study [12]. Model validation, however, is done using non-standard drive cycles from on-road testing, as a chassis dynamometer is not readily available for extended periods of time. The EPA calculates the forces experienced by a vehicle with a different set of parameters than C_{rr} and C_dA_f as previously explained. There are published dynamometer target coefficients which can be used to determine the road load experienced by a vehicle as a different approach. These dynamometer target coefficients capture the road load experienced by the vehicle and are calculated by doing a coast down test. The coast down test is where the vehicle is at speed on road and placed in neutral; then allowed to decelerate with no brake pedal applied capturing the dissipative load experienced by the vehicle. In order to determine the tractive force requirements a vehicle inertia term is added based on vehicle weight. For real-world, off dynamometer testing it is important to consider the impact of grade even if the net elevation change is zero. Equation 6 should yield the same result as Equation 1; the answer is simply reached by a different method. The A, B, and C terms are a curve fit with terms proportional to exponential powers of vehicle velocity. The EPA target A is most closely related to C_{rr} while the EPA target C is adjusted with C_d as it is related to the square of velocity. The B term is proportional to velocity, which takes into account a second coefficient (c_{rr_1}) of rolling resistance that is not considered for this case.

$$F_{tr} = A + B * V + C * V^2 + mgsin(\theta) + mM_i \frac{dV}{dt} \qquad (6)$$

The one improvement by Equation 6 instead of Equation 1 is there is a term that scales with velocity, which does have an impact of the road load experienced by the vehicle. Some models disregard the second coefficient of rolling resistance or the 'B' term and try and capture it using just a modified A and C. The major limitation is in how the three parameters of A, B, and C are determined. The three terms are a curve fit that matches vehicle coast-down data from on road testing, on the dynamometer, which means that target numbers are unique for a vehicle and a set of operating conditions. If the initial test weight changes, lower rolling resistance tires are installed, or aerodynamic changes are made, there can be no direct insight gained using the EPA method, other than re-running the coast down test.

Equation 6 is still a time based calculation, (for this study 1 Hz) way of calculating the forces experienced by a vehicle. Table 3 gives the target coefficients used to calculate the forces experienced by the vehicle. Note that the standard EPA units are using pounds-force (lbf) and velocity (mph). In the model these units are converted to the international system (SI) units.

Table 3: EPA Dynamometer Target Coefficients Used

	English	**SI**
A	**26.91** $\boldsymbol{lbf}$	**120** $\boldsymbol{N}$
B	**0.4670** $\boldsymbol{\frac{lbf}{mph}}$	**4.65** $\boldsymbol{\frac{N}{m/s}}$
C	**0.02438** $\boldsymbol{\frac{lbf}{mph^2}}$	**0.543** $\boldsymbol{\frac{N}{m/s^2}}$

The testing at EPA was conducted differently than it would have been for a federal certification test. Because EPA offered testing to all 16 EcoCAR teams, which had extensively modified the vehicle, no coast down data was available for each specific vehicle. In order to save time, a set of A, B, and C parameters were established for all of the vehicles to use. This only takes into account the dissipative forces known as road load. The dynamometer requires another input in inertial mass, to apply the proper inertial force for each drive cycle. The A, B, and Cs used for the VT_{REX} were for an inertial test mass of 4500 lbs, while the VT_{REX} inertial test mass was 5000 lbs. The dynamometer was given the ABCs for a 4500 lbs Crossover SUV and then was given an inertial test mass of 5000 lbs. In short the dynamometer was not applying the correct road load force that the vehicle should experience in real world driving. Because the ABCs are for a lighter weight vehicle, the road load force experienced by the vehicle during EPA testing is less than experienced on road. Table 4 shows the values of C_{rr} and C_d that were originally assumed in the model based on data supplied by GM. After correlating the ABCs used, the adjusted column is what the vehicle C_{rr} and C_d should be for real world driving. These numbers will be used to calculate rear world range, energy consumption, and the energy weighted drive cycle averaged efficiencies.

Table 4: Model validation from EPA data

	Model	Adjusted
Coefficient of Rolling Resistance (C_{rr})	0.009	0.0060
Coefficient of Aerodynamic Drag (C_d)	0.417	0.353

As previously mentioned a set of ABCs is only valid for a particular vehicle weight and set of vehicle parameters (aerodynamic drag and rolling resistance). In an attempt to capture the road load replicated by the dynamometer for vehicle testing and validation a new C_{rr} and C_D must be calculated. This needs to be done because the dynamometer applied a different tractive force than the vehicle actually experienced in real life, because of the mass differences and the fact that the coast down data was not matched to the dynamometer target coefficients. It should be noted that for a normal vehicle, the EPA test data set that is readily available is acceptable to be used for most model validation. If the testing was done correctly for the vehicle, this step is not needed. Table 5 shows the previously validated real world C_{rr} and C_D against the values that will be used to validate the testing done on the dynamometer at EPA.

Table 5: Model validation parameters for EPA data only.

	Real World	EPA Test
Coefficient of Rolling Resistance (C_{rr})	0.0060	0.0054
Coefficient of Aerodynamic Drag (C_d)	0.353	0.348

Using the EPA test C_{rr} and C_D a plot of vehicle speed and road load power has been generated against the EPA model of ABCs using Equation 6. Figure 7 shows a graphical representation of the two different methods. Notice that because of the adjusted terms for C_{rr} and C_D that the curves are identical, which is desired.

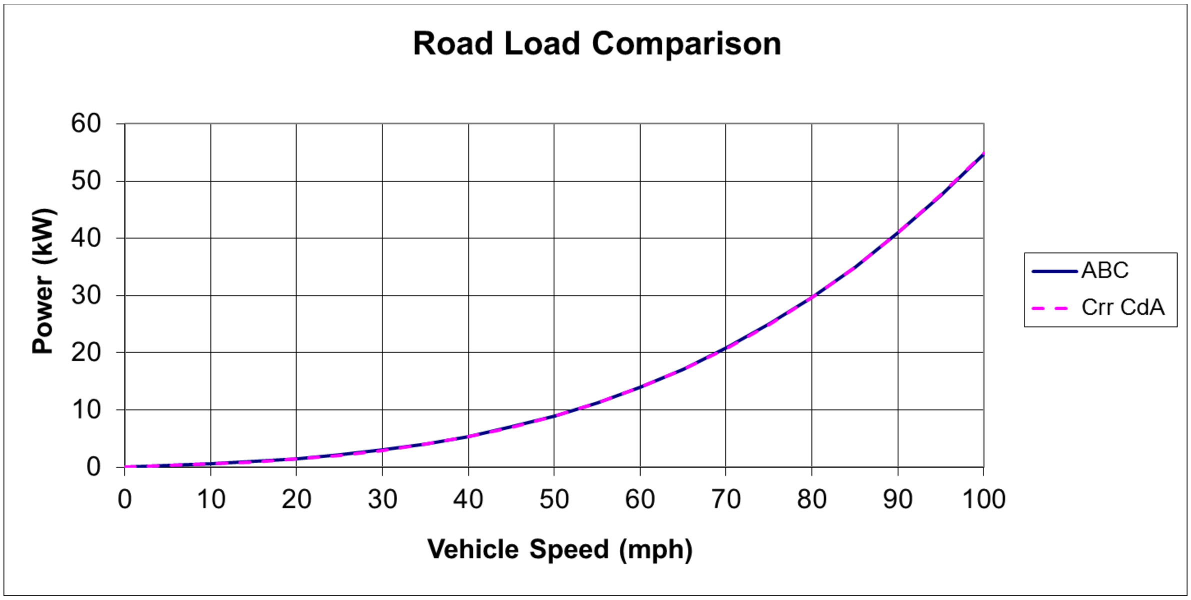

Figure 7: Plot of Road Load Power vs. Speed for different modeling approaches

For model validation, the real world parameters, while they reflect the true vehicle characteristics cannot be used to compare the vehicle to EPA data. The adjusted values from Table 4 are used in this study to validate the non-standard drive cycles. Table 5 shows the adjusted C_{rr} and C_d that matches the A, B, and C parameters used at EPA. Remember that adjusting the C_{rr} and C_D is not the right way to model vehicle force equations when scaling mass, but in order to use the data collected from EPA, the assumption is that the lower C_{rr} and C_d will accurately capture the tractive energy requirements and give valid results for vehicle energy consumption. Any results that have been collected and presented from EPA testing are lower in energy consumption because of the lower vehicle forces required to overcome. The final range prediction and estimated EV energy consumption for a given drive cycle will be based on the C_{rr} and C_d from Table 5 real world data, not the EPA test data. The results from Table 5 are only used to validate the prediction of the model against the testing performed at EPA, as this is the only time that the VT_{REX} had on a chassis dynamometer.

3.2 Drive Cycle Modes

There are three main states for a vehicle during a drive cycle: propelling, braking, and idle. For an electric or plug-in hybrid electric vehicle, there is also a final state: charging. In this state, the powertrain is disabled but energy is flowing into the vehicle from the electric grid to recharge the battery. Understanding thsee states and losses that go with the individual component efficiencies that make up the hybrid powertrain gives the designer insight into possible improvements.

3.2.1 $F_{tr} > 0$: Propelling

With a positive tractive effort term, energy is required from the vehicle powertrain. The energy required at the wheels is less than what is required from the rechargeable energy storage subsystem (RESS) because of losses associated with non-ideal driveline components. A nuance of the propelling case is a powered deceleration, when the vehicle is decelerating but requires propelling energy from the vehicle. This case is most easily demonstrated when the vehicle slows down approaching a stop light, but would stop sooner than desired, so the driver requests power from the drivetrain while the vehicle is slowing down. Another example is an underpowered vehicle climbing a grade, such as a heavily loaded freight truck. The vehicle is putting power to the road, but because of the grade, it is still losing speed. Figure 8 is the Urban Dynamometer Drive Schedule (UDDS) with propel demands identified in red. Note that propel, braking, and idle portions of time are somewhat unique to each vehicle and its properties.

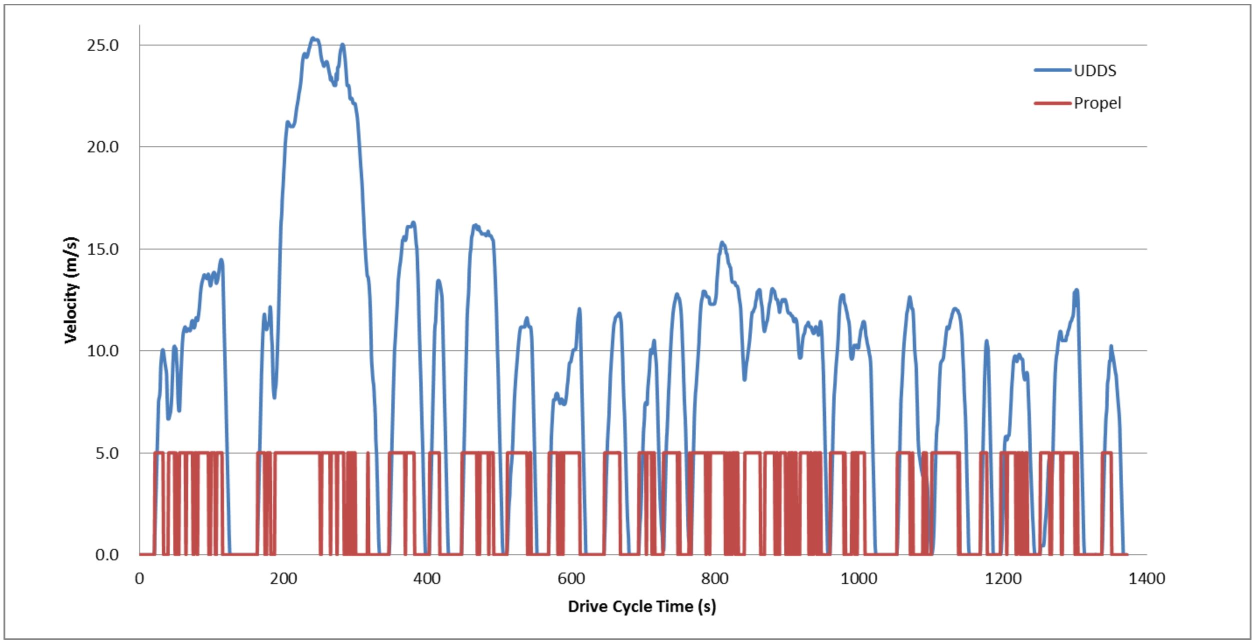

Figure 8: UDDS with propel times identified

3.2.2 $F_{tr} < 0$: Braking

For an electrified vehicle powertrain, a negative tractive effort term is an opportunity to recover energy that is stored as kinetic energy due to vehicle movement or potential energy from climbing a grade. However, the vehicle must always overcome the losses from rolling resistance and aerodynamic drag, even during braking. Regenerative braking is never completely ideal, and all vehicle powertrains are also equipped with friction brakes that convert the kinetic energy into heat as opposed to electricity. The main reason for splitting the energy flow into propelling and braking cases is to properly account for losses while recharging the RESS during regenerative braking. The correct energy consumption term for a drive cycle can be determined by the change in RESS energy over vehicle distance traveled. However, without splitting the energy flow into the two separate power flow directions, the component losses and accessory load are not clearly accounted for. While regenerative brake energy recovery does reduce total vehicle energy consumption, speed and power limitations prevent it from being sufficient for all braking requirements. Figure 9 is a plot of the HWFET drive cycle with braking points identified.

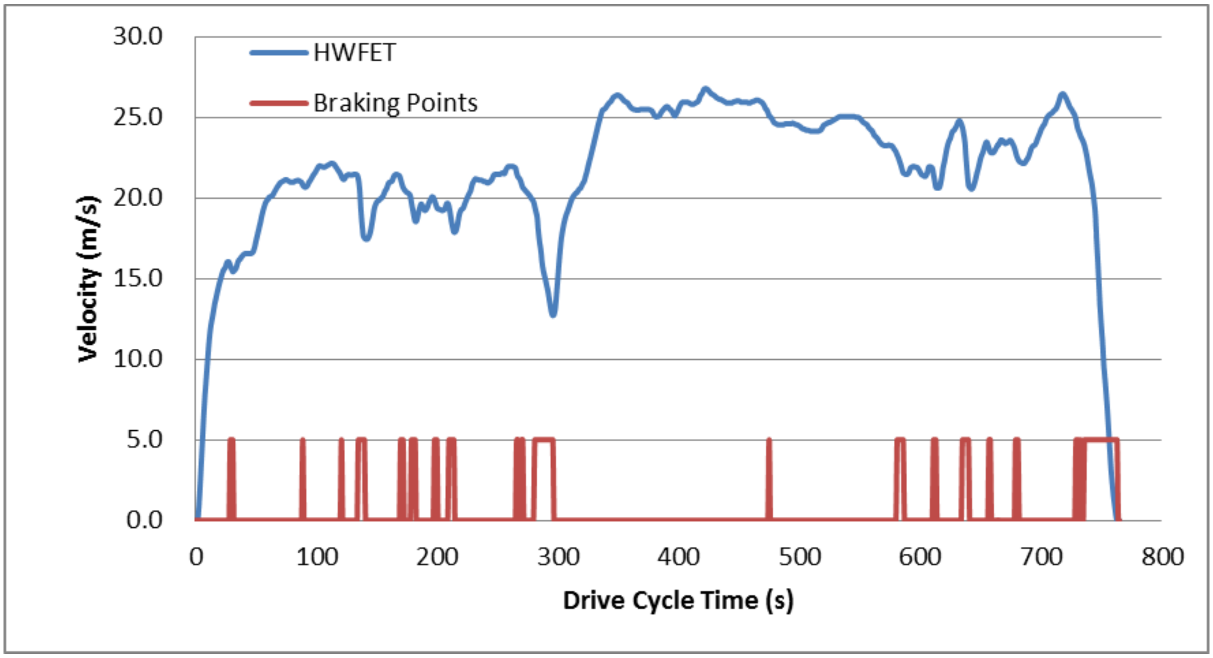

Figure 9: HWFET with braking times identified

3.2.3 $F_{tr} = 0$: Idle

When the powertrain output is zero while the vehicle is stationary, energy is still being consumed on board. An electric vehicle still has an accessory load requirement used to supply power to headlights, control modules, and other electrical components. For a given cycle the accessory load may not require much energy, but is still present. Figure 10 shows the US06 drive cycle with the idle times called out.

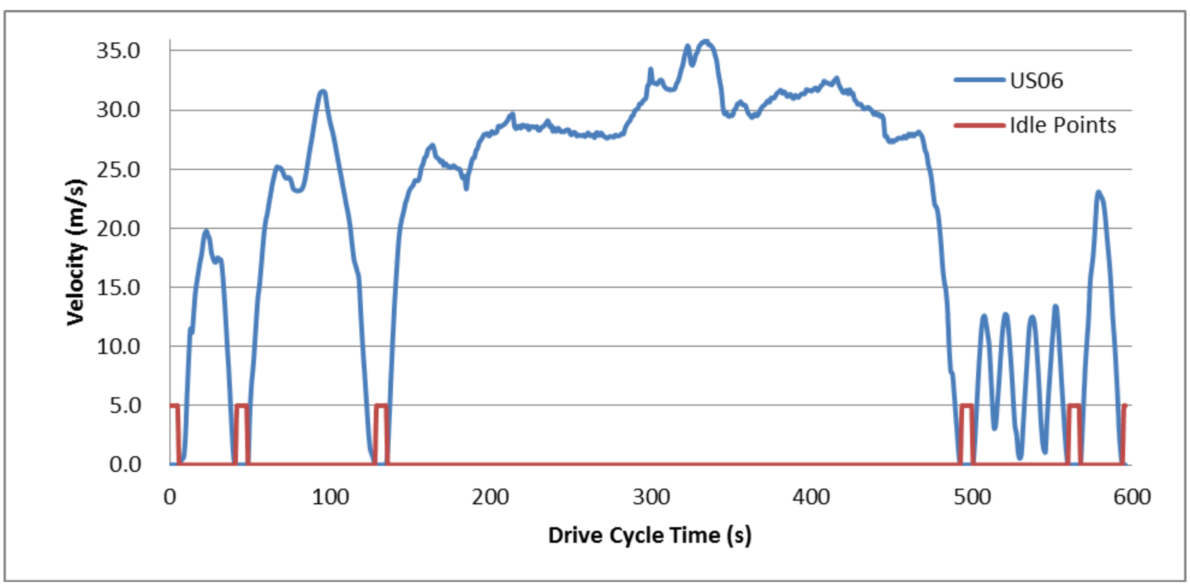

Figure 10: US06 with idle times identified

3.2.4 Charging

For an EV or PHEV with a charge depleting (CD) range, grid electric energy must be put back into the RESS for later propulsion use. During charging, there are losses associated with the internal resistance of the battery pack, the high voltage battery charger, and vehicle accessory loads including battery thermal management. Electric vehicle energy consumption can be rated in AC Wh/km referring to the grid electric energy needed to fully recharge the RESS based on the DC Wh/km used to complete the drive cycle.

3.3 Model Setup

Everything up to this point has been about finding the tractive force requirement at the wheels. Using the methods described for splitting force demands into propelling, braking, and idle along with Equations 1-5 above the tractive force requirements at the wheels can be calculated using the data supplied in Table 6. The data supplied in Table 6 is for the validation of real world non-standard drive schedules. Only the C_{rr} and C_D will change to the values in Table 5 when validating the EPA data.

Table 6: Vehicle Parameters used to determine Tractive Energy Requirements

Test Mass, m (kg)	2270
Inertial Mass Factor, Mi	1.04
Drag Coefficient, C_d	0.353
Frontal Area, A_f (m^2)	2.64
Rolling Resistance, C_{rr}	0.006
Density of Air, ρ (kg/m^3)	1.2
Gravity, g (m/s^2)	9.81

The first step is to establish the drive cycles used for the energy analysis. For this paper, results for UDDS, '505', HWFET, and US06 are reported. Using the velocity vs. time trace for the drive cycle, the model identifies the propelling, braking, and idle time based on the calculated tractive effort from Equation 1. Table 7 shows the results for the four cycles of interest. Total cycle time is standardized, while the breakdown of propelling and braking times may vary slightly depending on vehicle glider properties.

Table 7: Time breakdown for cycles of interest (s)

	Propelling	Braking	Idle	Total
UDDS	758	370	244	1372
'505'	279	132	94	505
HWFET	675	86	4	765
US06	414	147	35	596

The power required to overcome the tractive effort for rolling, aerodynamic drag, and inertia (grade also if available) can be calculated using Equation 7 below. Equation 7 can be applied to the individual forces and split into propelling, braking, and idle cases by applying the logic explained in the previous section. The energy required to propel the vehicle is the sum of the power terms over each one second time step for the propelling case (Eq. 8) and the braking case (Eq. 9). Note that this simple approach is only valid for 1 Hz data; if 10 Hz data is applied, the summation will need to take into account the smaller time step. Equations 8 and 9 show the energy terms required for the analysis, where the positive and negative exponents denote propelling and braking energy respectively.

$$P_{tr}[kW] = F_{tr} * V \left[kN * \frac{m}{s}\right] \tag{7}$$

$$E_{tr}^{+}\,[Wh] = \sum P_{tr}^{+} \tag{8}$$

$$E_{tr}^{-}\,[Wh] = \sum P_{tr}^{-} \tag{9}$$

The tractive energy required at the wheels to propel and brake the glider vehicle up to this point are shown in Table 8. To be clear, the glider vehicle has no powertrain losses and is 100 % efficient. Note also that at this point there is no idle energy, because the powertrain is not (yet) supplying an accessory load.

Table 8: Tractive Energy at the wheels for a Glider (Wh)

	Propelling	Braking
UDDS	1940	-1090
HWFET	2280	-340
US06	3170	-1160

The force requirements for the tractive effort are broken down into rolling, aerodynamic, inertia and grade terms in Equation 1. Remember that the standard cycles (UDDS, HWFET, and US06) do not contain grade. The information from Table 9 supports that improving just one part of the tractive effort equation will reduce energy consumption but will not have the same impact across all cycles in terms of percentage reduction in energy consumed. Grade was not included into Table 9 because for this portion of the study no energy was used, since there is no grade present in the standard cycles. The color coding of the table is used to bring attention to the lowest use of energy (green), the intermediate consumer (yellow), and the portion of the forces that uses the most energy (red).

Table 9: Propelling Energy brake down for cycles of interest

	Tires	Aero	Inertia
UDDS	17 %	17 %	66 %
505	15 %	25 %	60 %
HWFET	25 %	54 %	21 %
US06	12 %	41 %	47 %

3.4 Application of Sovran's 2003 Model to Glider Energy Consumption

Sovran uses a set of 6 coefficients that are matched to the energy consumption for the vehicle glider, as seen previously in Table 5. There are 3 parameters for propelling α, β, and γ, and there are 3 parameters for braking α', β', and γ'. Sovran does not account for grade or a second coefficient of rolling resistance, and as such another set of parameters have been included into Equations 10 and 11, λ and Δ. As a reminder *m* is vehicle mass and *S* is the cycle distance. Since the inertial forces sum to zero, the energy consumed in propelling and braking the vehicle due to inertia all identical. For this reason it is acceptable to treat γ and γ' as the same number. The parameters are have units as given in Table 10, and can also be found in the nomenclature section at the beginning of this paper.

$$E_{tr}^{+} = \frac{mS}{1000}\left(\alpha c_{rr_0} + \Delta c_{rr_1} + \beta\frac{C_D A_f}{m} + \gamma M_i + \lambda Grade\right)\ [MJ] \quad (10)$$

$$E_{tr}^{-} = \frac{mS}{1000}\left(-\alpha' c_{rr_0} - \Delta' c_{rr_1} - \beta'\frac{C_D A_f}{m} + \gamma M_i - \lambda Grade\right)\ [MJ] \quad (11)$$

3.4.1 Calculating the Original Sovran Parameters

While typical numbers for mid-size sedans of Sovran's parameters are given in his 2003 paper, there is a way to derive each of the individual parameters if the energy split for each component is known and in the form of propelling and braking. This is why it is so important to understand the equations given up to this point, as now the parameters can be derived to use in Sovran's model as long as the energy terms are in the right category. Results for the energy of each drive cycle as given in Table 8 and using the vehicle glider properties as specified in Table 6 can be seen in Table 10.

Table 10: Original Sovran Parameters for Modeled Vehicle

		UDDS	HWFET	US06	Units
Propelling	α	6.870	8.757	7.692	$\frac{m}{s^2}$
	β	100.8	284.1	380.6	$\frac{kg}{ms^2}$
	γ	0.1697	0.0489	0.1837	$\frac{m}{s^2}$
Braking	α'	2.936	1.055	2.121	$\frac{m}{s^2}$
	β'	30.69	26.36	81.37	$\frac{kg}{ms^2}$
	γ'	0.1697	0.0489	0.1837	$\frac{m}{s^2}$

3.4.2 Effect of Grade on Tractive Energy Requirements at the Wheels

Grade is not considered by the Sovran model, as it is not included in the EPA certification test procedure. Grade is a force that the vehicle experiences and is included in Equations 10 and 11 to account for real world driving conditions. At a very basic level, grade is a change in elevation or height from one time step to the next. Table 11 shows the results for vehicle tractive energy requirements at the wheels, time spent in powered decelerations, and the calculated Sovran parameters for the cycle. These results can be compared against Table 12 which shows the same information for a constant 5 % grade. While it is not typical to experience a constant 5 % grade, it is important to note that the tractive energy requirements in the propelling state increases by 250 % for the UDDS. The brake energy that is available for recapture through regenerative braking decreases by 40 % for the UDDS. Notice that because of the relationship between grade and C_{rr} that α and λ for a constant grade are the same. This will not always be the case as is demonstrated by Table 13. A special condition in coast, where the tractive effort at the wheels is zero, but the vehicle is at speed rarely happens, and has not been seen in this work.

Table 11: Results for standard drive cycles with a 0 % (flat) road

	UDDS	HWFET	US06
Powered Decel (s)	90	201	98
Propel Energy (kJ)	6.798	8.062	11.185
Brake Energy (kJ)	-3.788	-1.190	-4.016
α	6.880	8.798	8.818
β	100.906	285.339	383.940
γ	0.1696	0.0481	0.1820
α'	2.932	1.014	2.069
β'	30.60	25.05	78.01

Table 12: Results for standard drive cycles with a 5 % grade (hill)

	UDDS	HWFET	US06
Powered Decel (s)	292	269	157
Propel Energy (kJ)	17.536	25.019	23.089
Brake Energy (kJ)	-1.587	-0.335	-2.015
α	8.788	9.597	8.818
β	125.7	306.5	432.9
γ	0.1166	0.0222	0.1351
λ	8.788	9.597	8.818
α'	1.017	0.211	0.993
β'	5.78	3.93	29.06
λ'	1.017	0.211	0.993

What is more interesting to look at is the effect of a positive and negative grade term, and the return to the same elevation at the end of the drive cycle, such as what might happen on an on-road test loop. For a simple modeling exercise consider that for the first half of the drive cycle the vehicle is going up a 5 % grade, and the last half the vehicle is coming down a 5 % grade. Figure 11 shows a graph of elevation in meters for a UDDS. The elevation starts out at zero and increases due to a 5 % grade until a timestamp of 539 s at which point a -5 % grade is employed. Because the cycle uses 1 Hz data the net elevation change is ended up at 0.7 m, and could not reach zero.

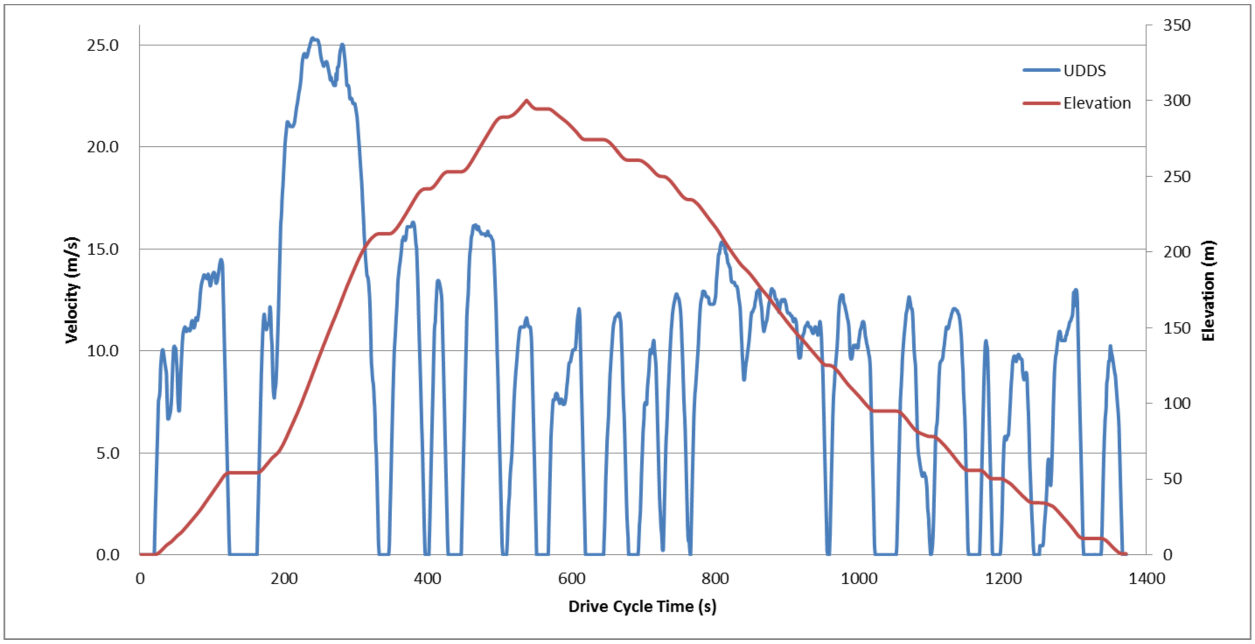

Figure 11: Elevation change using a $\pm$ 5 % Grade for a UDDS

While the results in Table 13 are useful to understand grade contributions, note that depending on when the grade is applied the results will be different. For instance if the vehicle had started out going downhill and then back up the grade so that total elevation change was near 0, the results would be different. There are some unique concepts to grasp that are shown by Equations 12, 13, and 14 for the Sovran model. These concepts can be used to verify that the correct answer was calculated.

$$\lambda + \lambda' = 0 \quad \text{for a cycle with no net elevation change} \tag{12}$$

$$\alpha + \alpha' = g \tag{13}$$

$$\gamma = \gamma' \tag{14}$$

Table 13: Results for cycles that include grade with near zero change in elevation

	UDDS	HWFET	US06
Powered Decel (s)	113	123	76
Propel Energy (kJ)	9.975	12.929	13.592
Brake Energy (kJ)	-6.950	-6.056	-6.443
α	5.265	5.012	5.550
β	97.720	140.555	247.813
γ	0.1181	0.0322	0.1625
λ	3.6540	4.6689	3.4603
α'	4.545	4.798	4.260
β'	33.79	169.85	214.11
λ'	-3.6427	-4.6681	-3.4749
Elevation Change (m)	0.7	0.1	-1.0
Time when grade switches (s)	539	409	301

3.5 HEVT Requirements and installed components

For this model, a front wheel drive electric vehicle is used as seen in Figure 12. The electric vehicle model consists of a battery, motor/controller, and driveline. In the propelling state the RESS supplies energy to power the accessory loads and to the electric motor which converts electrical energy to mechanical energy which is then transferred to the wheels by a driveline. At each point along the way, the energy supplied by the RESS is reduced by the inefficiency of the components. The opposite energy flow occurs during braking. A negative amount of energy is available at the wheels, which may be reduced by friction brakes if needed and then traverse the energy flow path back to the RESS. At each step along the way, the amount of energy going back into the pack shrinks because of the losses in the powertrain. Often, the proper accounting of losses is lost when only the net positive flow of energy through the powertrain is considered. Thus, the proper definition of efficiency should be used for each component depending on the power flow direction for propelling or braking.

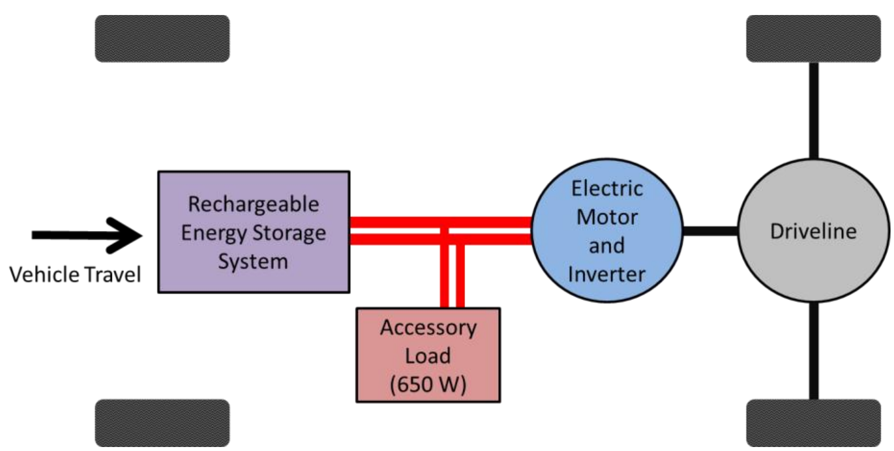

Figure 12: Vehicle Component Layout

Table 14 shows the component efficiencies and vehicle glider parameters used for this study. The component efficiencies will change as needed to illustrate the impact on battery sizing for the design case. The RESS used is a custom battery pack designed by HEVT using Lithium Iron Phosphate ($LiFePO_4$) cells. The electric motor is a 125 kW machine with a single speed 7.17:1 gear reduction. The mass used for the electric vehicle powertrain in this model is higher than normal because the validation vehicle also has a 2.4L FlexFuel engine acting as a range-extender mounted on the front axle of the vehicle, in addition to the battery mass. The test mass of 2270 kg is empty vehicle weight with two passengers. The mass used later in the validation section of the report will reflect the vehicle weight for testing done at EPA as well as the predicted weight for the EcoCAR competition event: Emissions and Energy Consumption (E&EC).

Table 14: Modeling Parameters used for a Crossover EV

Test Mass, m (kg)	2270
Inertial Mass Factor, Mi	1.04
Drag Coefficient, C_d	0.35
Frontal Area, A_f (m^2)	2.64
Rolling Resistance, C_{rr}	0.006
Tire Rolling Radius (m)	0.35
Density of Air, ρ (kg/m^3)	1.2
Gravity, g (m/s^2)	9.81
Motor Overall Gearing	7.17
Drivetrain efficiency	0.96
Motor efficiency	See Eqn. 20,21
RESS efficiency	See Eqn. 31
Regen Fraction	0.85
Useable SOC	0.90
Accessory Load (W)	650
Charging Efficiency	0.88

Table 15 shows the requirements set out for the design stage of the electric vehicle. As the battery is sized to meet the range requirement, the impact on acceleration and vehicle mass will be reported as well. A simplified model for the battery that scales internal resistance, power, and energy capacity of the RESS with mass is used.

Table 15: EV Requirements

Range, combined City/Highway unadjusted (km)	80
Acceleration time, 0-100 kph (s)	< 12
Battery Power (kW)	> 140
Trace miss for UDDS and HWFET	No

3.6 Energy Consumption Model

All of the calculations done so far in the model have just been about calculating the minimum amount of energy and power at the wheels to meet the drive cycles. This is, of course, the lowest energy consumption value possible for a drive cycle, as at this point the vehicle powertrain is assumed to be 100 % efficient. The minimum energy consumption for completing the three standard drive cycles is shown in Table 16. These numbers will only increase as non-ideal powertrain efficiencies and energy losses are included.

Table 16: Minimum energy consumption (Wh/km)

	Net	Propel	Braking
UDDS	67	159	-92
505	84	169	-85
HWFET	113	134	-21
US06	151	242	-91

3.6.1 Energy Weighted Efficiency

It is imperative that the concept of energy weighted drive cycle average efficiency. The following set of equations will show in detail the difference between energy weighted, and time weighted efficiencies and the energy balance used. Efficiencies are a way to capture the losses due to mechanical, thermal, and other imperfections in a system and relate input to output energy requirements of a device. The basis of this thesis is understanding the losses of each powertrain component so having the correct losses accounted for is a major goal of this work. Using an energy weighted efficiency makes sure that the input energy is equal to the output energy plus the losses thus following the law of conversation of energy. Equation 15 shows how to calculate the energy weighted efficiency, note that the efficiency should always be less than 1.

$$\eta_{energy,avg} = \frac{E_{output}}{E_{\text{input}}} \tag{15}$$

This defines the energy weighted efficiency calculation

Another approach would be the mathematically integrate based on time the efficiency to a time weighted average efficiency. The concept of time weighted averaging can be seen in Equation 16, which will not yield the correct losses, and thus violate the first law of thermodynamics (conversation of energy). Furthermore in the case of this work when the terms are split into propelling and braking the time weighted average number will be very small if the entire cycle time is taken into account instead of just the time spent propelling or braking the vehicle. Table 17 is a summary of the three possible efficiencies and the predicted losses as a result. Uses the energy weighted drive cycle average efficiency is the only one that yields the correct losses and thus the correct output energy. This concept will be validated in later sections.

$$\eta_{time,avg} = \int \eta_i \tag{16}$$

This defines the time weighted efficiency calculation

Table 17: Comparison of Propel Motor Efficiency terms for a UDDS

	Energy In (Wh)	Efficiency	Losses (Wh)	Energy Out (Wh)
Energy Weighted		0.86	300	1820
Time Weighted (1372 s)	2120	0.43	1210	910
Time Weighted (732 s)		0.80	420	1700

3.6.2 Driveline, Friction Brakes, and Regen Fraction

This approach will look at the road and work back up the energy path to get to the battery pack. Before the energy can be transferred from the wheels on the front axle, it must first go through a driveline. The driveline in the test vehicle consists of a single mechanical input from the electric motor, 2 sets of gear pairs internal to the transmission, an open differential, and 2 mechanical constant velocity (CV) axles. According to the manufacturer of the transmission each gear pair is 98 % efficient at peak operation conditions. Since there are two gear pairs, an estimate of 96 % efficiency for the transmission and the total driveline. The validation section later in this paper will show that, the assumption of achieving peak efficiency is not valid. Figure 13 shows the energy required at the wheels, and the energy into and out of the driveline that is supplied or accepted by the electric motor. Equations 17 through 19 show how the energy at the driveline is calculated from the wheels. Blue will be used consistently throughout this paper to visualize the propelling case, and green is used to display the braking case. 'E' is used to show energy flows through components and 'L' is used to show losses.

$$E_{pr,dl} = \frac{E_{pr}}{\eta_{pr,drive}} \tag{17}$$

This defines the energy required to propel at the driveline

$$E_{br,regen} = \zeta * E_{br,Brakes} \tag{18}$$

This defines the energy available after losses to heat in friction braking

$$E_{br,dl} = \eta_{br,drive} * E_{br,regen} \tag{19}$$

This defines the energy available at the driveline for the braking case

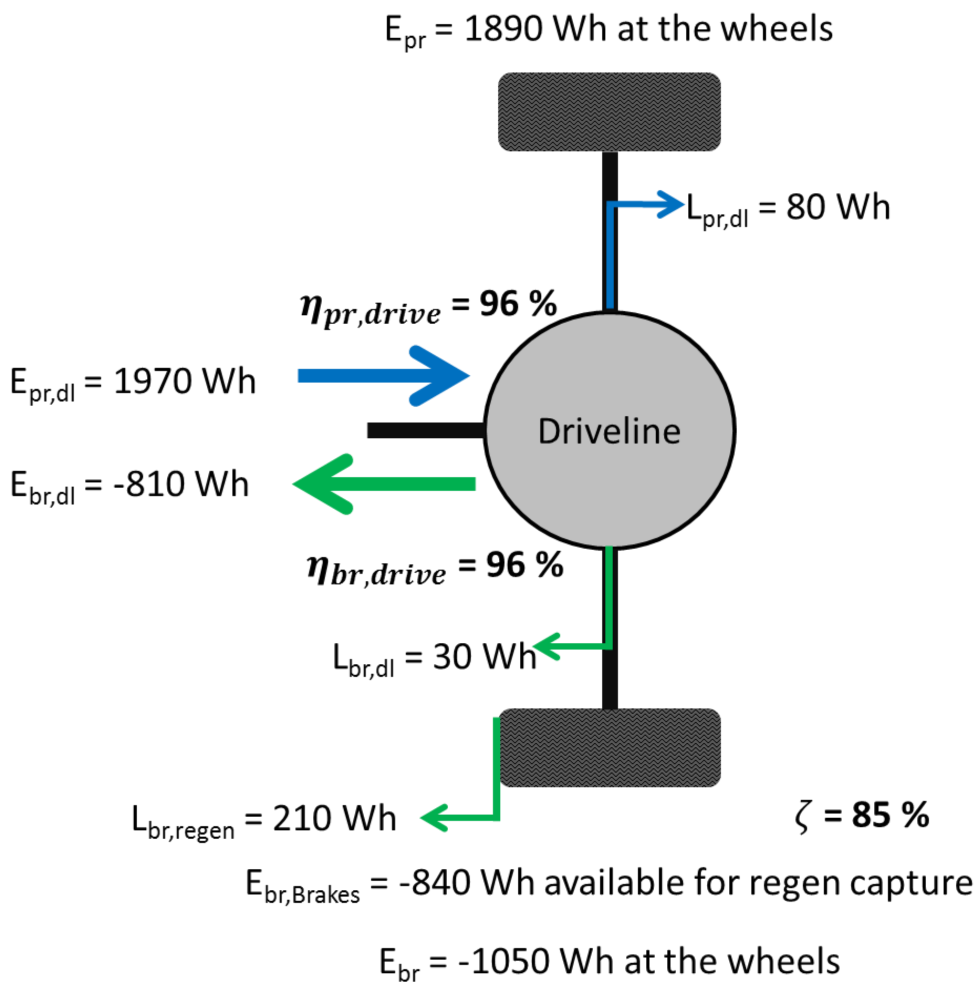

Figure 13: Propelling and Braking energy flow: UDDS, Driveline

Component efficiencies are given for both propelling and braking driveline conditions, as well as a friction braking efficiency. It is unreasonable to assume that the vehicle can recapture 100 % of the energy available at the wheels for two reasons. The first reason is that in a PHEV application when the vehicle leaves the garage with a full charge, there is no way for the electric motor to act as a generator to slow the vehicle down by making electricity. The second is that for emergency stopping conditions friction brakes are still used in hybrid electric vehicles. For safety, the vehicle needs to be able to stop even if the high voltage system is not active, if that is a mode of operation for the vehicle platform. The VT_{REX} has no way of preventing the friction brakes from engaging when the brake pedal is pressed. A negative torque request is sent to the electric motor (regenerative braking) very early in the brake pedal apply, but competition rules prevent us from modifying the mechanical hydraulic braking system installed.

3.6.3 Electric Motor

The 125 kW motor has a peak torque output of 300 Nm. The motor on the test vehicle is geared directly to the ground through a single speed gear reduction transmission of 7.17:1. Using the information supplied from the manufacturer for torque and speed, motor power and efficiency can be calculated from the tractive effort at the wheels. From motor rotor speed, gearing, and wheel radius, vehicle speed can be calculated as the vehicle overcomes forces applied by the road. Using the given velocity and time points for the EPA drive cycles, vehicle acceleration can be calculated, which can be translated to rotor speed. This model assumes no wheel slip, and that the motor operates as an ideal electric motor with constant torque through base speed (3,000 RPM) and constant power after the base speed.

Using an equation adapted from Larminie [24], it is possible to create an efficiency map for the electric motor based on a few parameter values. Equation 20 gives an equation that can be used to determine motor efficiency for the propel case for a permanent magnet machine, if the correct constants are applied. Equation 21 is similar but is for the braking case, when the motor acts as a generator and commands negative torque to create electricity from the mechanical energy. Table 18 gives an insight into the parameters used to make Figure 14 match Figure 15 which is the supplied efficiency data from UQM.

$$\eta_{motor,pr} = \frac{Output\ power}{Output\ power + losses} = \frac{T\omega}{T\omega + K_c T^2 + K_i \omega + K_w \omega^3 + C} \tag{20}$$

$$\eta_{motor,pr} = \frac{Output\ power + losses}{Output\ Power} = \frac{-T\omega}{-T\omega + K_c T^2 + K_i \omega + K_w \omega^3 + C} \tag{21}$$

Table 18: Motor Efficiency Constants

Parameter	Value	Description
K_c	10800	Copper Losses
K_i	8.38	Iron Losses
K_w	7062	Windage Losses
C	600	Constant Losses

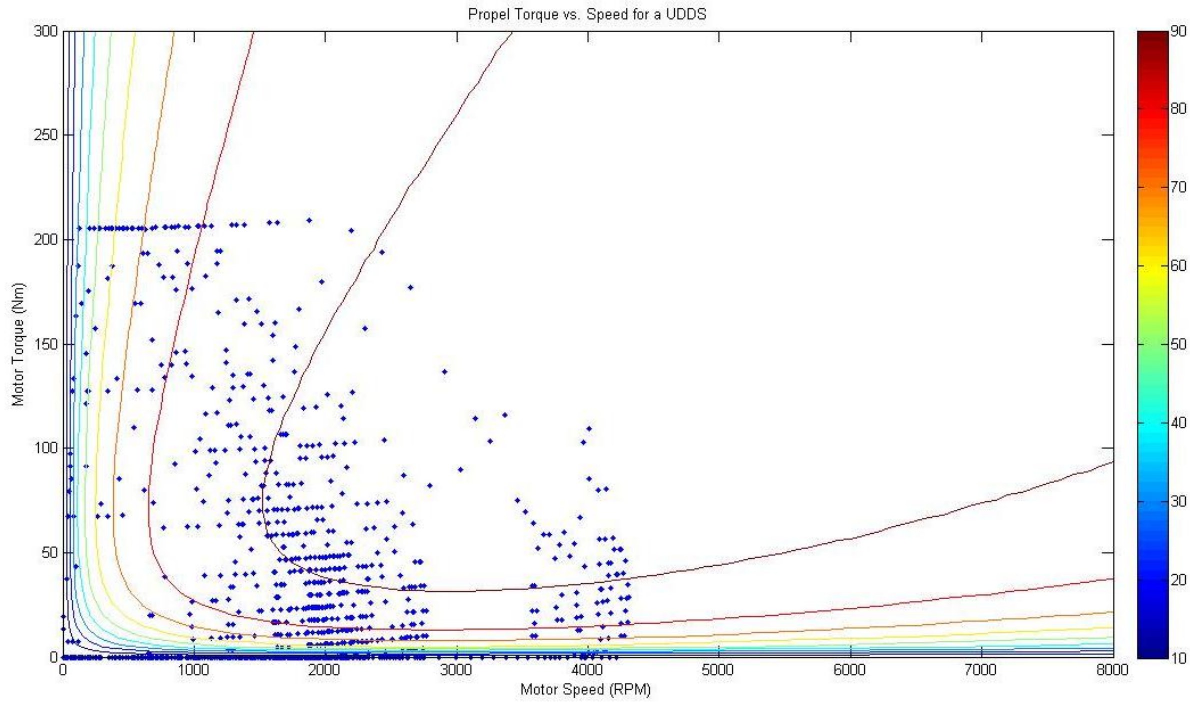

Figure 14: Quadrant 1 Torque vs. Speed Efficiency map using Equation 18 for UDDS

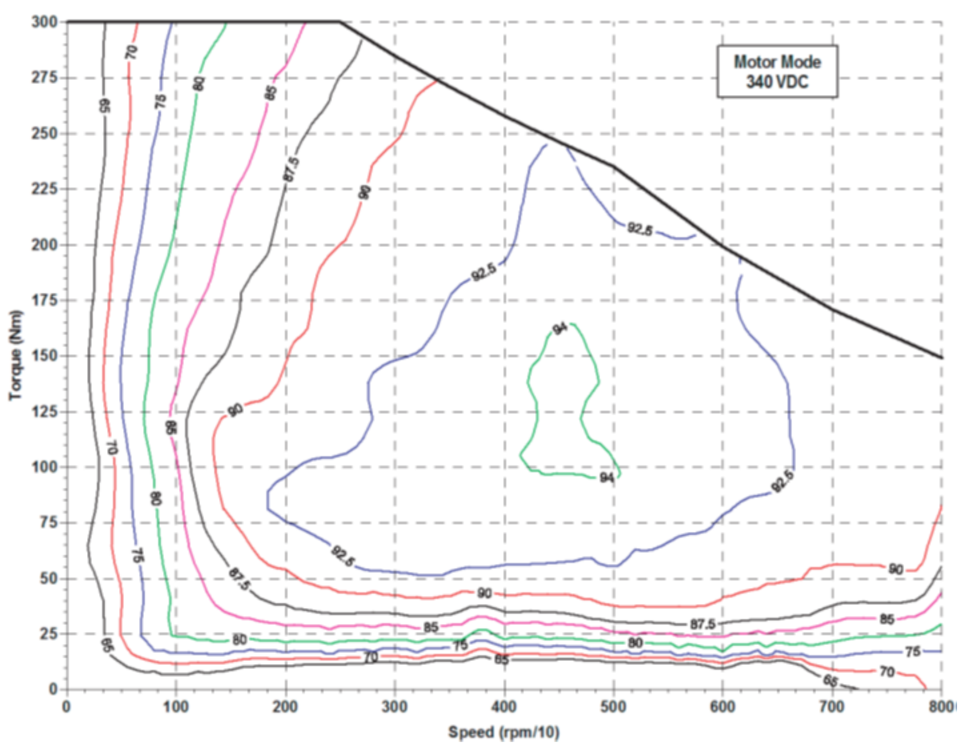

Figure 15: Efficiency Map supplied by UQM for their 125 PowerPhase Motor

The motor efficiency equations (Eq. 20 and Eq. 21) need torque and speed in order to determine efficiency. Equation 22 shows how to calculate rotor speed using the vehicle average velocity and the N per V parameter which is a function of gearing and wheel radius. Equation 23 and 24 show how to calculate motor power and torque at each time step. Remember to follow the guidelines establish by Equations 8 and 9 and keep the terms split into propelling and braking terms. Useful information can be collected at this point as well, such as maximum and minimum motor power, torque, and speed. Now that the torque and speed of the motor are known, Equations 20 and 21 can be used to calculate the efficiency of the motor or generator at each time step. Note that the motor efficiency used is an energy weighted average drive cycle efficiency, not a time average. Meaning that the end user cannot simply average all of the motor efficiency points for propelling and get the correct answer when dealing with energy. Figure 16 shows a detailed look into the energy flow, losses, and efficiency for the propelling and braking states of a UDDS. Apply Equations 17 and 19 in a similar manner to account for the efficiency and losses.

$$S_{motor}\,[rpm] = V_{AVG}\left[\frac{m}{s}\right]\left(\frac{N}{v}\left[\frac{rpm}{\frac{m}{s}}\right]\right) \tag{22}$$

$$P_{motor}\,[kW] = \frac{P_{tr}}{\eta_{dl}} \tag{23}$$

$$T_{motor}\,[Nm] = \frac{P_{motor}}{S_{motor}}\left|\frac{1000 * 30}{\pi}\right| \tag{24}$$

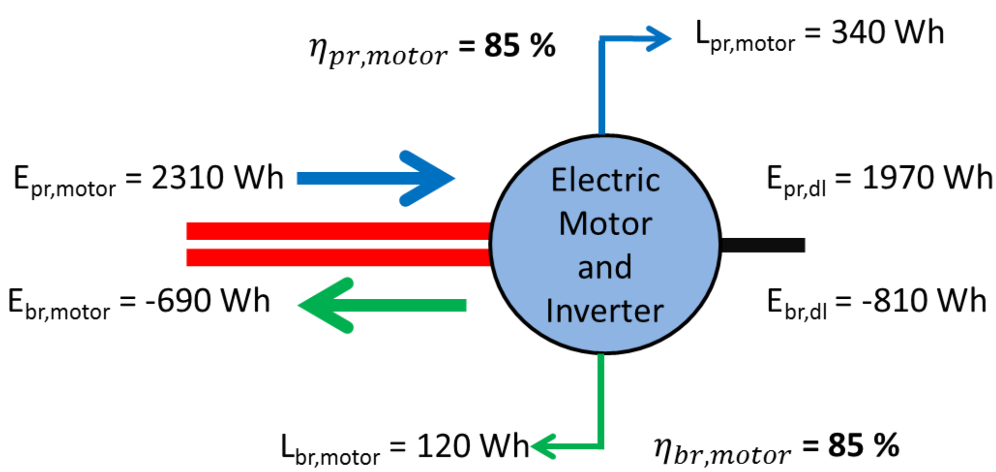

Figure 16: Propelling and Braking energy flow: UDDS, Motor

3.6.4 Accessory Load

The accessory load is an always present parasitic electrical draw on the vehicles RESS. As seen in Figure 17, the electrical accessory load is modeled at 650 W. The energy consumed by accessory load is split up into three categories, propelling, braking, and idle. The accessory load is modeled to be about 1.8 A at 360 V nominal on the high voltage battery pack, which is just current coming out of the RESS. The accessory load on the vehicle is fed through a DC/DC converter which takes the 360 V nominal and steps it down to automotive 12 V (13.8 under charge). For the propelling case, this is fairly straightforward as it just adds to the energy coming out of the battery pack. The same is true for the braking case, in that before the energy from the wheels is stored in the RESS some energy is siphoned off to feed the accessory load. Even during idle, energy is still being consumed, and has been split out to keep the energy flow of propelling and braking to just when the vehicle is at speed.

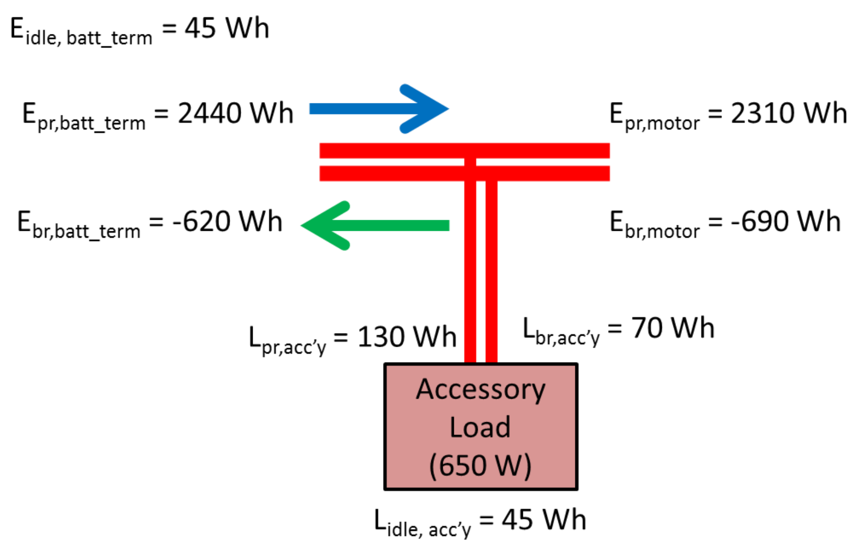

Figure 17: Propelling, Braking and Idle energy flow: UDDS, Accessory Load

3.6.5 Rechargeable Energy Storage Subsystem

There are two battery type choices available for sizing a RESS: energy or a power pack. The pack is sized to meet power requirements with energy capacity as a secondary consideration. First, the pack must be able to supply enough power to meet the drive cycle requirements. Next, the battery must be able to supply peak power to the motor after all losses and accessory loads are considered. If both an energy and a power pack are suitable and the same mass, choose the one with more energy capacity. The sizing is a function of mass, and the energy densities used are given in Equations 25 through 29. Using the information and the peak power required for the cycle, a battery mass with the most energy capacity can be selected [25].

$$\text{Energy Pack: } E_{CAP}\ (\text{kWh}) = m_{battery} * .12 \tag{25}$$

$$\text{Power Pack: } E_{CAP}\ (\text{kWh}) = m_{battery} * .075 \tag{26}$$

$$\text{Energy Pack: Power (kW)} = m_{battery} * .4 \tag{27}$$

$$\text{Power Pack: Power (kW)} = m_{battery} * 1.2 \tag{28}$$

$$R_{int}\ (\Omega) = 1.2/\ E_{CAP} \tag{29}$$

For this model a RESS mass of 267 kg, with a nominal energy capacity of 20 kWh (18 kWh useable), and a peak available power of 320 kW is used. Figure 17 quotes the energy that comes into and out of the terminals of the RESS, but that is not the energy that goes into the internals of the RESS. The RESS has an internal resistance, as given in Equation 29, that can be used along with the open circuit voltage (V_{oc}) to calculate current (A) requirements to meet the power demand as shown in Equation 30. Based on the internal resistance model given, it is also possible to calculate the RESS Voltage under load as given in Equation 31. The energy lost due to internal resistance can be calculated as in Equation 32 for propelling, braking, and idle as shown below. Equation 33 describes the battery efficiency calculation, which can be used for propelling, braking, or idle. Figure 18 shows a graphical representation for the RESS, energy weighted drive cycle averaged efficiency, energy flow, and losses, for the propelling and braking case. Internal resistance losses for idle are neglected for this drive cycle as they as extremely small.

$$I\,[A] = \frac{V_{oc} - \sqrt{V_{oc}^2[V] - 4R_{int}[\Omega]P_{BATT_{TERM}}[kW]\left|\frac{1000\ W}{1\ kW}\right|}}{2R_{int}} \tag{30}$$

$$V\,[V] = V_{oc} - R_{int}I \tag{31}$$

$$L_{batt\_int}[kW] = R_{int}I^2\left|\frac{1\ kW}{1000\ W}\right| \tag{32}$$

$$\eta_{batt} = \frac{E_{batt\_term}}{E_{batt\_int}} \tag{33}$$

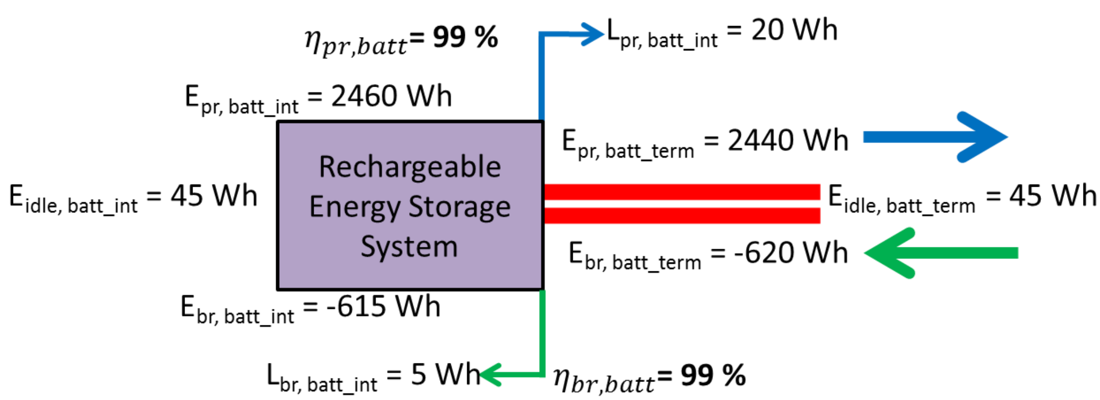

Figure 18: Propelling and Braking energy flow: UDDS, RESS

3.6.6 Powertrain Efficiencies

The model developed has the capability to determine the minimum required power and energy to complete a drive cycle, known as the tractive energy at the wheels. The propelling, braking, or idle state can be found by inspecting the power requirements for a given time step. For this analysis, a motor and generator efficiency equation is used as given by Equation 20, a driveline efficiency of 96 % is assumed, the useable energy of the RESS is 90 % change in SOC

(100 % SOC initially with a 10 % SOC lower limit), battery efficiency dependent on internal resistance (close to 99 %), a regenerative brake fraction of 85 %, and an accessory load of 650 W must be supplied to the vehicle at all times. Note that the efficiencies do not, and are generally not the same for the propelling and braking cases. This approximation was only done until the model could be validated an a good estimate of the proper drive cycle energy weighted propelling and braking efficiencies could be calculated. All of this information is required to determine the overall energy required from the terminals of the battery pack, for the second by second analysis. But for overall design insight, the energy consumption at the terminals can be calculated using a set of energy weighted propelling and braking efficiencies as shown in Equation 34 through 38. As a summary, Figure 19 displays the individual component efficiencies and energy losses at each component for a UDDS.

$$\eta_{pr} = \frac{E_{pr}}{E_{pr,batt\_term}} \tag{34}$$

This defines the energy weighted drive cycle averaged propelling efficiency

$$\eta_{br} = \frac{E_{br,batt\_term}}{E_{br}} \tag{35}$$

This defines the energy weighted drive cycle averaged braking efficiency

$$E_{cycle}\ [Wh] = \frac{E_{pr}}{\eta_{pr}} + \eta_{br} * E_{br} + E_{idle,batt\_term} \tag{36}$$

This defines the total energy used over a given cycle

$$\eta_{net} = \frac{E_{tr}}{E_{cycle}} \tag{37}$$

This defines the energy weighted drive cycle averaged net efficiency

$$EC_{cycle}\left[\frac{Wh}{km}\right] = \frac{E_{cycle}\ [Wh]}{S_{cycle}\ [km]} \tag{38}$$

This defines the drive cycle averaged energy consumption

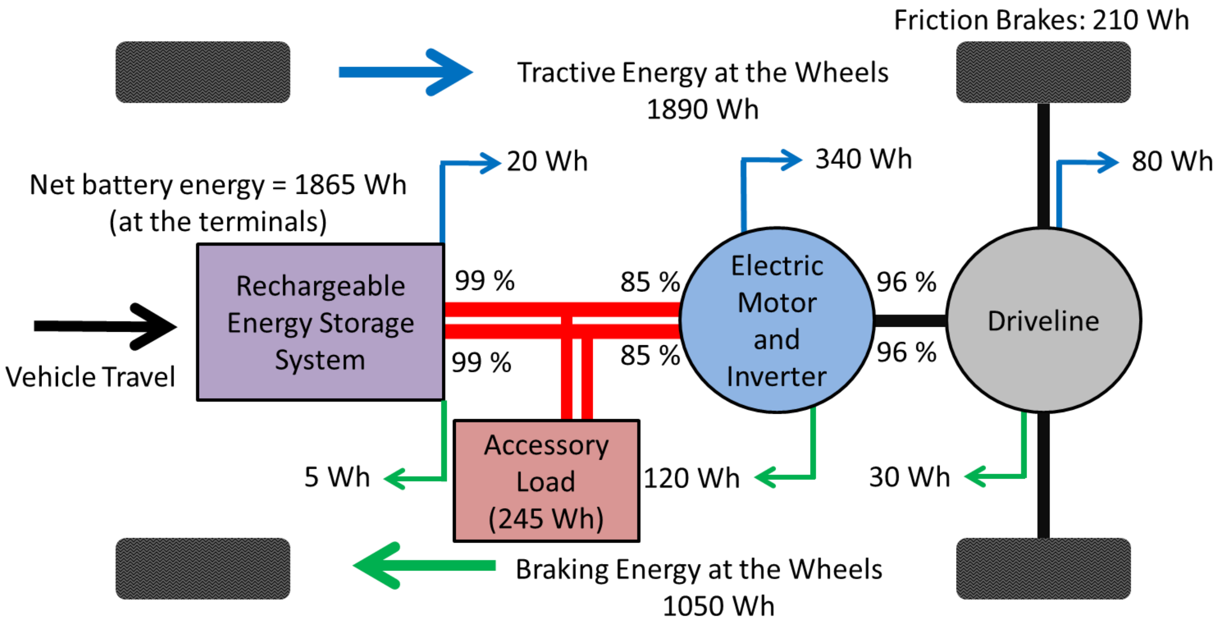

Figure 19: Display of Component Efficiencies and Losses for a UDDS cycle

Figure 20 is another way of representing the energy flow paths and losses for propelling and braking for an electric vehicle. Shown in blue is the propelling state, with the losses at each component showing up as height changes in the bar chart for an HWFET cycle. The energy flows through each component are the numbers used to calculate the energy weighted drive cycle averaged efficiencies at the components, propelling, braking, and net. Note that in the propelling case, there are no friction brakes being applied and the column is a place holder so that the columns line up with the braking case.

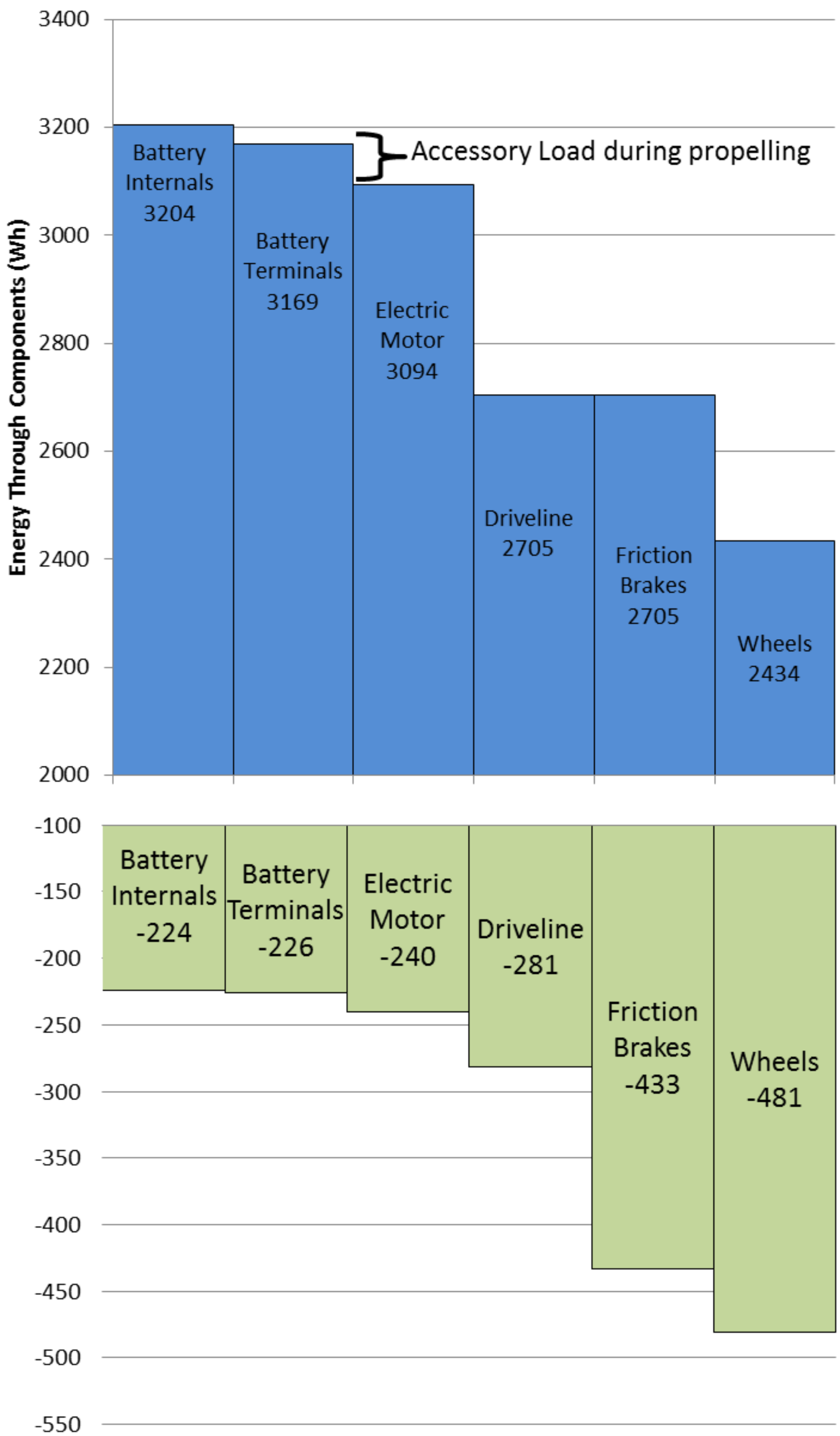

Figure 20: Energy Flow for the propel and braking states of the HWFET Cycle

3.7 EV Range

Now that the states of propelling, braking, and idle have been defined in theory and examples shown for the UDDS and HWFET in terms of energy flow and component losses, now a correlation to EV range can be made. The goal with the given vehicle powertrain is to reach an adjusted combined range of 80 km using the methods shown in Equation 39 and the previous sections. Equation 39 is based off of the CAFE unadjusted weighting which gives a slightly heavier weighting to city driving to calculate vehicle range. The standard is primarily used to calculate fuel economy, and is what automakers in the United States are held to.

$$Range_{unadjusted,combined} = 0.55Range_{UDDS} + 0.45Range_{HWFET} \tag{39}$$

The RESS selected for the VT_{REX} has a large amount of power and energy, and stores more energy than required to meet the goal of an 80 km range. In a design case the equations for sizing a battery to meet the power, energy, and weight requirements of a vehicle should be considered, but this study seeks to set up a design problem as well as validate the test vehicle. Using the parameters listed above, the following estimated range for a depletion of 90 % SOC (18 kWh) is listed in Table 19.

Table 19: Range prediction for the VT_{REX}

Cycle	Range (km)
UDDS	96.6
HWFET	97.1
Combined, unadjusted	96.8
US06	75.2

3.8 Charging

Since this electric vehicle is a PHEV, recharging the pack is required to restore the energy depleted out of the RESS. For the purpose of this study a high voltage (HV) charger that is nominally 92 % efficient is used. However, in an attempt to incorporate the losses of supplying accessory power to control modules on board to ensure safe charging of the high voltage battery, the charging process itself is only 88 % efficient from AC grid energy to DC energy stored in the RESS. A fully depleted pack (18 kWh) plugged into a 240 VAC, 20 A rated source (16 A continuous) with an average charging efficiency of 88 % will take 5.3 hours to charge. The time for the charge to complete assumes that the RESS accepts charge all the way to 100 %, and does not do any type of active balancing. This is not the case in real life, but for a simple time estimation, taking the DC energy put into the pack and estimating time to get a fully charged RESS is close. Energy consumption can now be related to AC grid energy, the results of which are shown in Table 20. Equation 40 demonstrates how to calculate the AC energy from the DC HV bus energy used.

$$EC_{AC} = \frac{EC_{DC}}{\eta_{charge}} \tag{40}$$

Table 20: DC and AC Wh/km for a given drive cycle

	DC Wh/km	AC Wh/km
UDDS	157	178
HWFET	156	177
Combined, unadjusted	157	178
US06	219	249

3.9 Conclusion

For any vehicle it is important to understand where the energy goes. The model that is setup in the previous sections details methods and equations to take known (or estimated) vehicle parameters and calculate the tractive effort required at the wheels for a given drive cycle. While the US EPA UDDS, HWFET, and US06 drive cycles are used the model primarily. A data set collected from real word driving conditions, including grade, can be used by this model. After the tractive effort required at the wheels is established, working up through the powertrain, losses at friction brakes, the driveline, electric motor and inverter, energy to feed the accessory load, and losses within the RESS are considered. Using this information, at last the EV range of the vehicle is predicted to be 97 km on a combined UDDS and HWFET drive schedule with a 90 % SOC swing. Finally, assuming that the RESS stays in bulk charge and does not do a balance charge, the RESS should take a little over 5 hours to recharge from a 240 V, 20 A rated AC wall outlet.

4. Validation of Results

The model built and explained in the previous section is based on engineering experience and some assumptions to get a baseline result. In order to further develop and improve the vehicle model developed, validation is performed using the VT_{REX} as previously described. While non-standard drive cycle testing has been done around Blacksburg and the surrounding area, the most useful data collected for model validation was done at an EPA test facility in Ann Arbor Michigan: National Vehicle Fuels and Emissions Lab. For the test given below the VT_{REX} was run on a 2-wheel drive dynamometer, as a pure electric vehicle. Three sets of test were run primarily, the first 505 seconds of a UDDS (for time), HWFET, and a full CD test which consisted of back to back UDDS cycles. Since the vehicle was running as a pure EV, there was no emission data collected for this section of tests. The vehicle was instrumented with 2 Hioki current clamps and a power analyzer. The first Hioki clamp was on the manual interrupt switch of the RESS, giving the power analyzer the ability to capture all of the current going into the terminals of the RESS. This clamp was in general a 200 A clamp, but during wall charge was replaced with a 20 A clamp, for increased resolution. A 20 A current clamp was also placed on the DC/DC converter HV input. Working under the assumption that the 12 V battery was always charged, the energy that the DC/DC requires from the HV bus can be used to directly calculate the accessory load for a cycle. The 2 wheel drive dynamometer imposes a force on the vehicle to simulate what the vehicle would experience on road. Shown in Figure 21 is diagram of the forces that the vehicle saw at the wheels for the UDDS cycle. For visualization the rolling resistance and aerodynamic drag has been multiplied by 10. This in conjunction with the vehicle speed trace is used to calculate power and energy requirements at the wheels. Remember that only the inertial term below the x-axis allows for the ability to recapture energy to store in the battery, and only after the rolling and aerodynamic drag and powertrain losses are correctly accounted for.

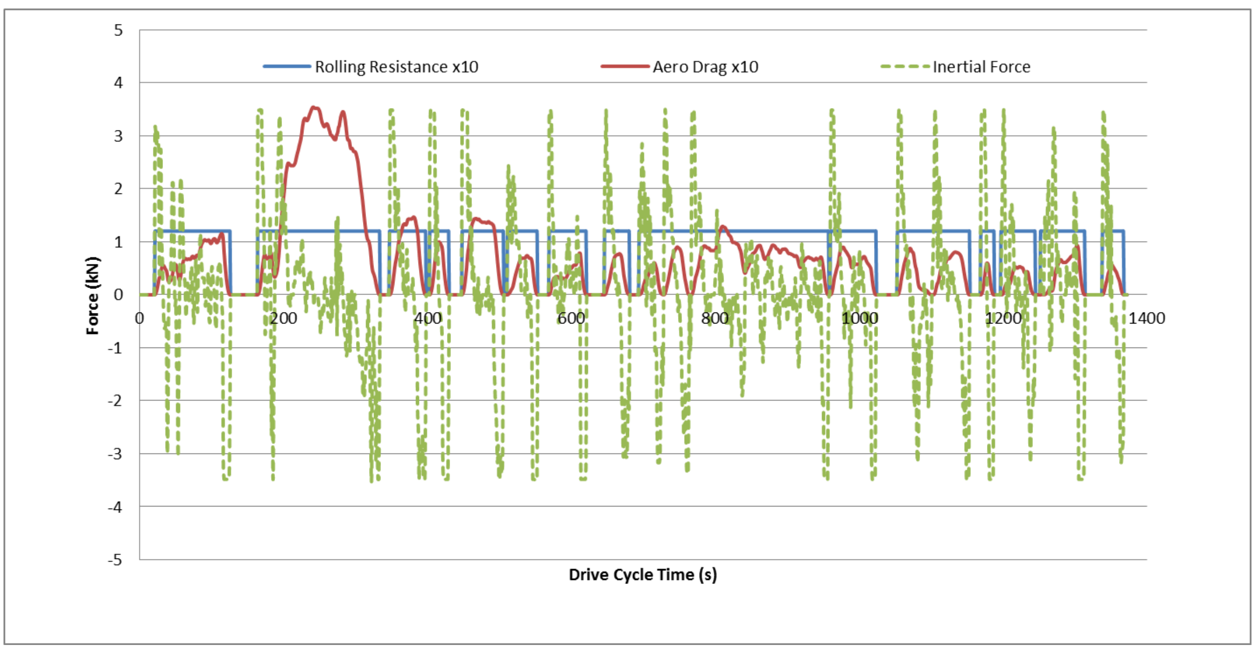

Figure 21: Forces Experienced by a Vehicle for a UDDS

The VT_{REX} logs data over the vehicle communication system and records this information for later analysis. Columns of interest in the vehicle data log include; RESS current (A), RESS voltage (V), RTM speed (RPM), RTM current (A), RTM voltage (V), DC/DC HV current (A), vehicle speed (m/s), and time (s). From this information the model calculates vehicle acceleration, power demand at each component, and powertrain use and losses. By keeping track of the energy in propelling, braking, and idle for each component it is possible to determine an energy weighted drive cycle averaged component efficiency. By comparing the energy available at the wheels to the energy at the terminals of the RESS to complete the drive cycle an energy weighted drive cycle averaged efficiency can be calculated as well. The next levels of this chapter will go into greater detail about the results, the impact on the model, and the limitation of the vehicle data collected. Table 21 shows the new and updated modeling parameters that are used to fit the model to the test data collected. Note that the major changes include using a propel and braking energy weighted efficiency term from the driveline, and including a motor idle load. The goal of this model is to predict the combined energy consumption correctly, so for simplicity the efficiencies listed below are for all cycles. If in the future more precision is desired, then the energy weighted drive cycle averaged efficiencies should be calculated for each cycle, rather than to meet the combined.

Table 21: New and Updated Model Parameters

Test Mass (kg)	2270
Inertial Mass Factor	1.04
C_d	0.35
A_f (m^2)	2.64
C_rr	0.006
Tire Rolling Radius (m)	0.353
Density of Air (kg/m^3)	1.2
Gravity (m/s^2)	9.81
Vehicle Gearing	7.17
Driveline Propel Efficiency	0.9
Driveline Braking Efficiency	0.65
Motor efficiency	Eqn 20
Grade (%)	0.00%
Regen Fraction	0.85
Accessory Load (W)	425
Charging Efficiency	0.88
Motor Idle Load (W)	225

4.1 505 Cycle Results

Dynamometer time at EPA's test facility was critical, so a decision was made to run just the first 505 seconds of a UDDS several times in order to accurately capture the city driving power requirements for the VT_{REX}. A trained EPA driver drove the cycle for the team, and Figure 22 shows the velocity vs. time trace for the cycle. The dashed green line is the federally regulated certification cycle, the red line is what the model predicts based on the speed trace collected on the physical cycle driven, and the dotted blue line shows data collected from the vehicle data logs. This convention will continue to be used for the rest of this report.

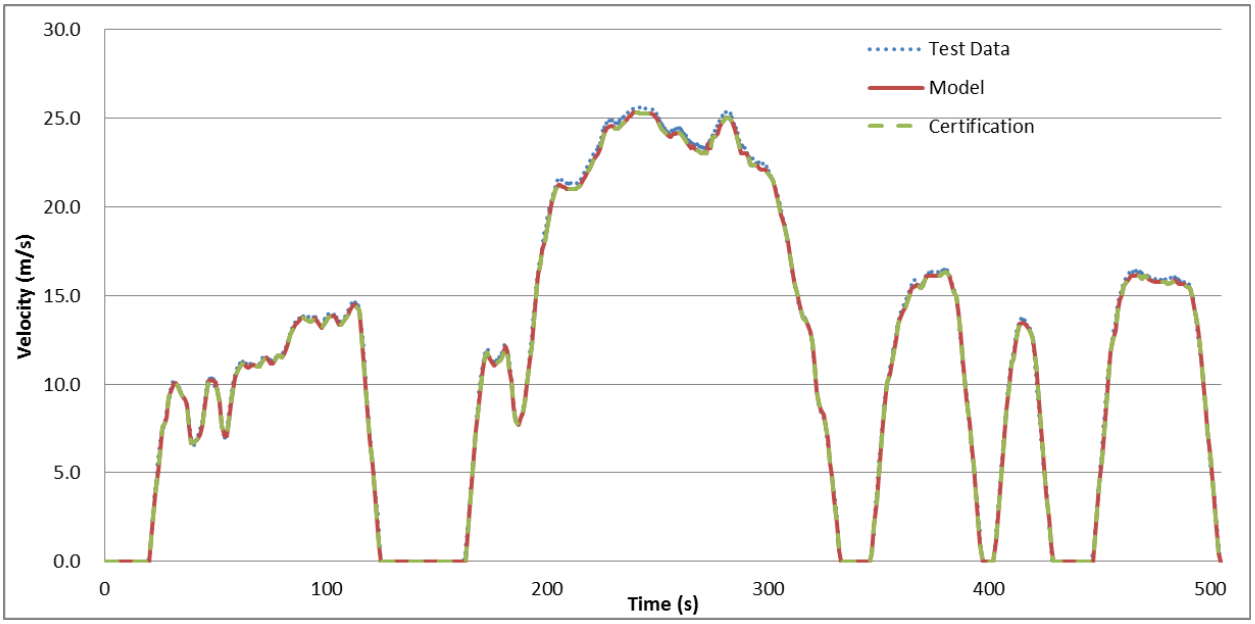

Figure 22: 505 Cycle Velocity vs. Time

The vehicle had no problem meeting and following the trace for the '505'. Normally during vehicle operation the team depends on a GM installed accelerometer to feed information on vehicle inertial forces to the controller to make decisions. Since the vehicle was strapped down to the dynamometer and stationary, the results for the accelerometer were not reliable. Because of this for validation the vehicle acceleration was found from the derivate of velocity trace for the drive cycle. The cycle data was recorded at 10 Hz, which generated quite a bit of noise in the calculation of vehicle acceleration. This is the biggest limitation of all of the data collected at EPA. According to the certification data the max acceleration is close to 1.5 m/s^2, however using the derivate approach the max acceleration for a .1 s (10 Hz) time step was found to be 4 m/s^2. While the scale of the inertial term is off, using this approach did lead to a total inertial force of 0 kN, which is to be expected. The result of the high accelerations and noise variations between acceleration and deceleration at constant speed has the effect of inflating the power required to overcome the inertial term, as well as peak motor power. In an attempt to combat this, and return valid results, the acceleration was smoothed out using a running average explained in Equation 41. Time step 2 is the current time, with 1 before and 3 being after the desired time. Using this smoothing technique the variation in accelerations still exists as can be seen in Figure 23 but the inflated energy required to overcome inertial forces was reduced to a number closer to the model.

$$\frac{dV}{dt} = \frac{\left(\frac{V_2 - V_1}{t_2 - t_1} + \frac{V_3 - V_2}{t_3 - t_2}\right)}{2} \tag{41}$$

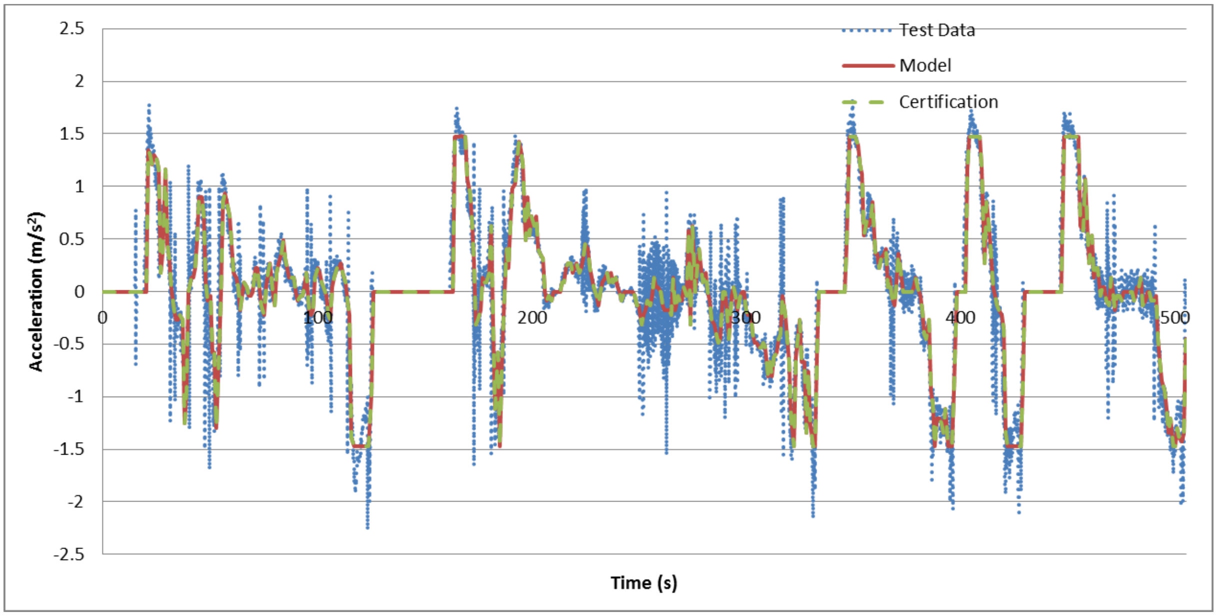

Figure 23: 505 Cycle Acceleration vs. Time

At this point, all of the numbers, equations, and parameters are available to calculate the tractive energy required at the wheels. Figure 24 shows the requirement for power at the wheels over the entire '505' cycle. Notice that the variations in power at the wheels follow the same spikes in the acceleration, which was already noted to be a limitation of this approach. Data above the x-axis represents time to propel while data below the x-axis is time spent braking. Time spent on the x-axis is representative of powertrain idle. Remember that at this point there is no powertrain information required; this is the glider requirements simply at the wheels. The summation of power required at the wheels gives an overall energy required to complete the cycle, which can be broken down into propelling and braking conditions.

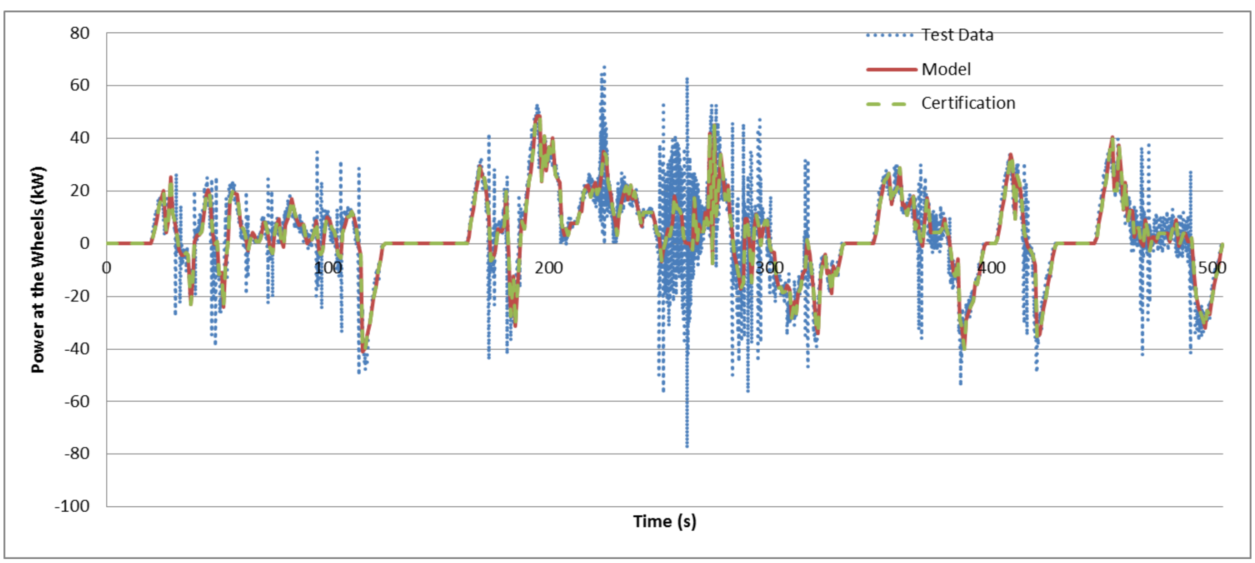

Figure 24: 505 Cycle Tractive Power at the Wheels vs. Time

The '505' cycle for the VT_{REX} at the given operating conditions has a propel time of 281 s, a braking time of 130 s, and an idle time of 94 s. This is shown graphically in Figure 25 with red being propel, blue being brake, and idle is represented by the presence of neither propelling or braking.

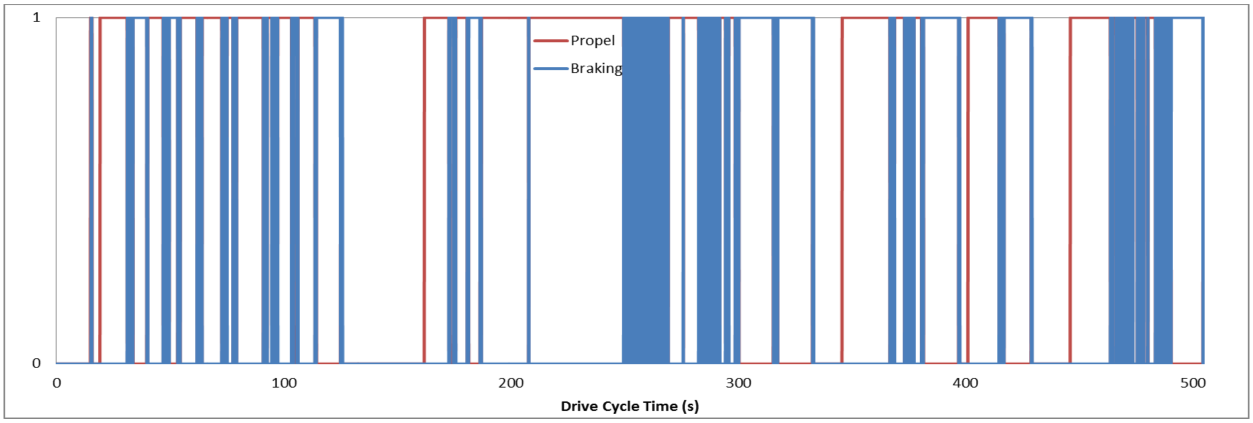

Figure 25: 505 Cycle Propelling, Braking, and Idle Time

Moving through the driveline losses for both cases, and friction brake losses in the braking stage, the motor output, or mechanical power can be seen in Figure 26. In looking through the test data, when the motor is enabled for traction there is a slight power draw on the high voltage bus. This power draw was required to simulate creep that a typical vehicle with an engine would have at low speeds. In an attempt to capture this feature at idle, a motor idle power term was added to the model. Through validation of both cycles a value of 225 W was determined to be required to have the motor idle in the test data match closely the modeled data. Another improvement to the model was to have a separate driveline propel and braking average efficiency rather than the same number in both directions.

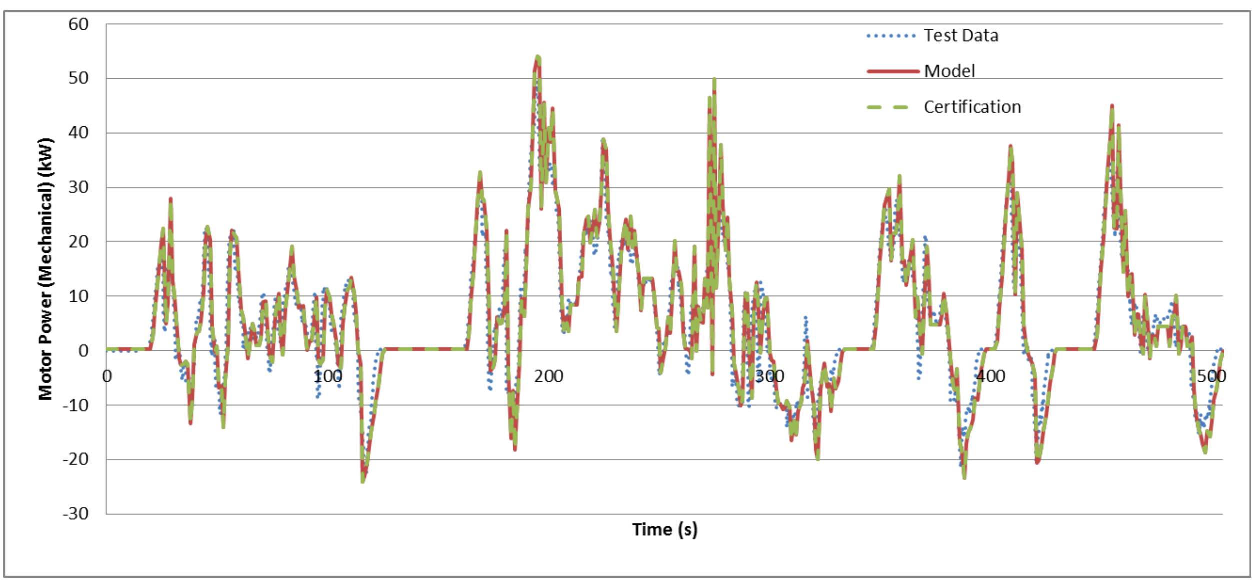

Figure 26: 505 Cycle Motor Output (Mechanical) Power vs. Time

Figure 27 shows a model of the electric motor torque required to meet the drive cycle trace when geared through the transmission to turn the wheels. This torque and speed is used with a set of motor parameters to determine an estimated motor efficiency that was tuned to match the data collected from vehicle testing.

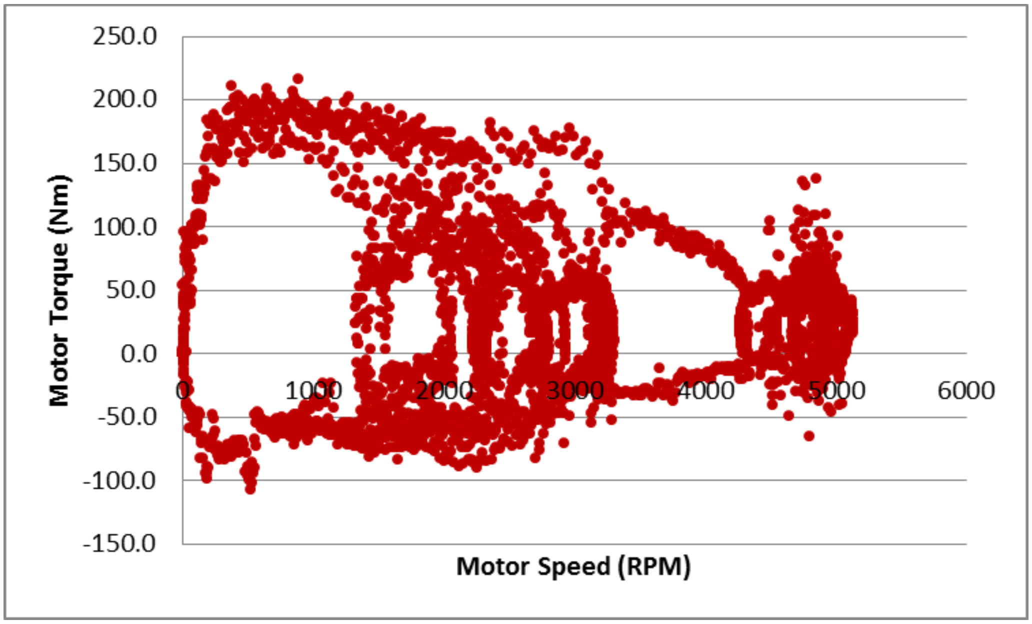

Figure 27: 505 Cycle Modeled Motor Torque vs. Speed

Going back to the powertrain configuration of the VT_{REX} validation vehicle, there is only the electric motor and accessory load being supplied energy from the RESS. Because of this the Power profile for the RESS, as seen in Figure 28 looks like a scaled version of Figure 26. The Accessory load modeled for this case, is a constant number, and does not vary based on pumps, fans, or other devices required by the vehicle for proper operation.

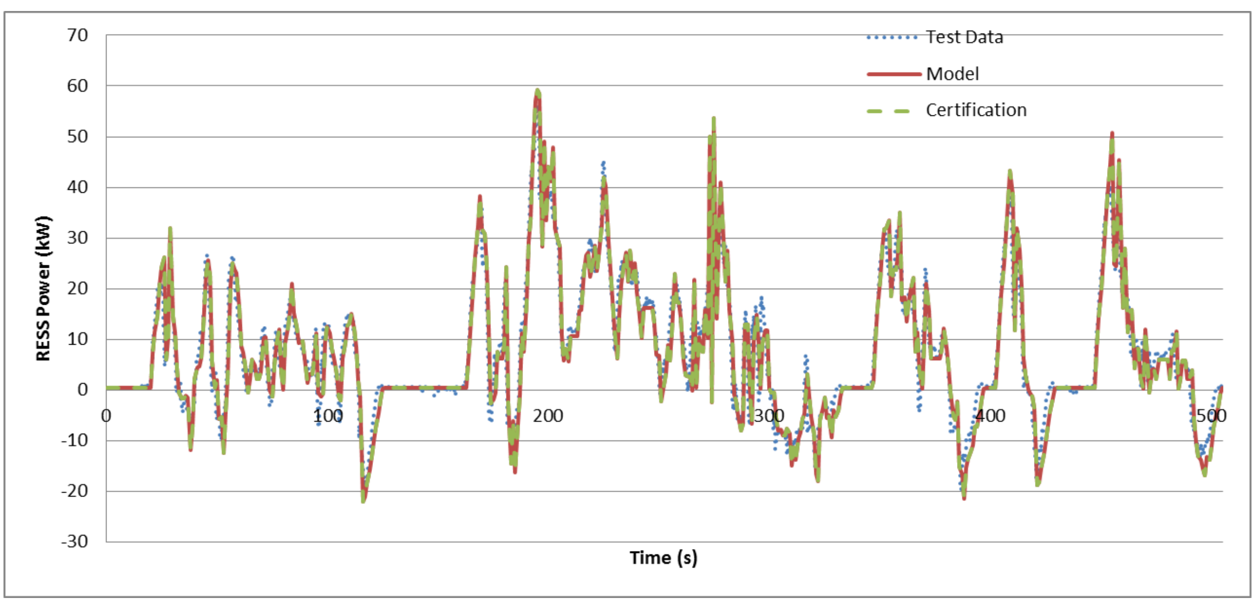

Figure 28: 505 Cycle RESS Power vs. Time

Table 22 through Table 24 display the data collected for the 505 vehicle test and compares the numbers against the model. This numbers are also validated against the HWFET figures and data shown in the next section of the paper. Remember that the goal within this research is to develop a model that can accurately represent the losses in each powertrain component, which can be used to find and calculate an energy weighted drive cycle average efficiency term for both propelling and braking, and finally to determine the energy use for a cycle. The energy weighted modeling efficiency numbers do not necessarily line up for the 505, but are a set of numbers to use to calculate the combined energy consumption of the vehicle. Figure 29 shows a visual representation of the information displayed in Table 22 and Table 23.

Table 22: 505 Cycle Energy Consumption

	505 Test Data				505 Model				505 Cert		
Energy	Propel	Braking	Idle		Propel	Braking	Idle		Propel	Braking	Idle
Wheels (Wh)	1075	-582	-		1075	-582	-		975	-488	-
Friction Brakes (Wh)	-	-524	-		-	-524	-		-	-440	-
Driveline (Wh)	1182	-248	-		1194	-340	-		1084	-286	-
Motor (Wh)	1204	-157	3		1354	-299	6		1240	-249	6
Battery Terminals (Wh)	1236	-141	13		1386	-282	16		1273	-233	17
Battery Internal (Wh)	1248	-139	13		1404	-280	16		1289	-232	17

Table 23: 505 Cycle Energy Losses

	505 Test Data				505 Model				505 Cert		
Losses	Propel	Braking	Idle		Propel	Braking	Idle		Propel	Braking	Idle
Friction Brakes (Wh)	-	58	-		-	58	-		-	49	-
Driveline (Wh)	108	276	-		119	183	-		108	154	-
Motor (Wh)	21	91	3		159	42	6		157	37	6
Accessory Load (Wh)	32	17	10		32	17	10		33	16	11
Battery (Wh)	12	1	0		18	2	0		16	1	0

Table 24: 505 Cycle Efficiencies

	505 Test Data			505 Model			505 Cert	
Efficiency	Propel	Braking		Propel	Braking		Propel	Braking
Regen: Eqn. 16	-	0.90		-	0.90		-	0.90
Driveline: Eqn. 15, 17	0.91	0.47		0.90	0.65		0.90	0.65
Motor: Eqn. 18,19	0.98	0.63		0.88	0.88		0.87	0.87
Battery: Eqn. 31	0.990	0.990		0.987	0.994		0.988	0.995
Total: Eqn. 32, 33	0.87	0.24		0.78	0.48		0.77	0.48

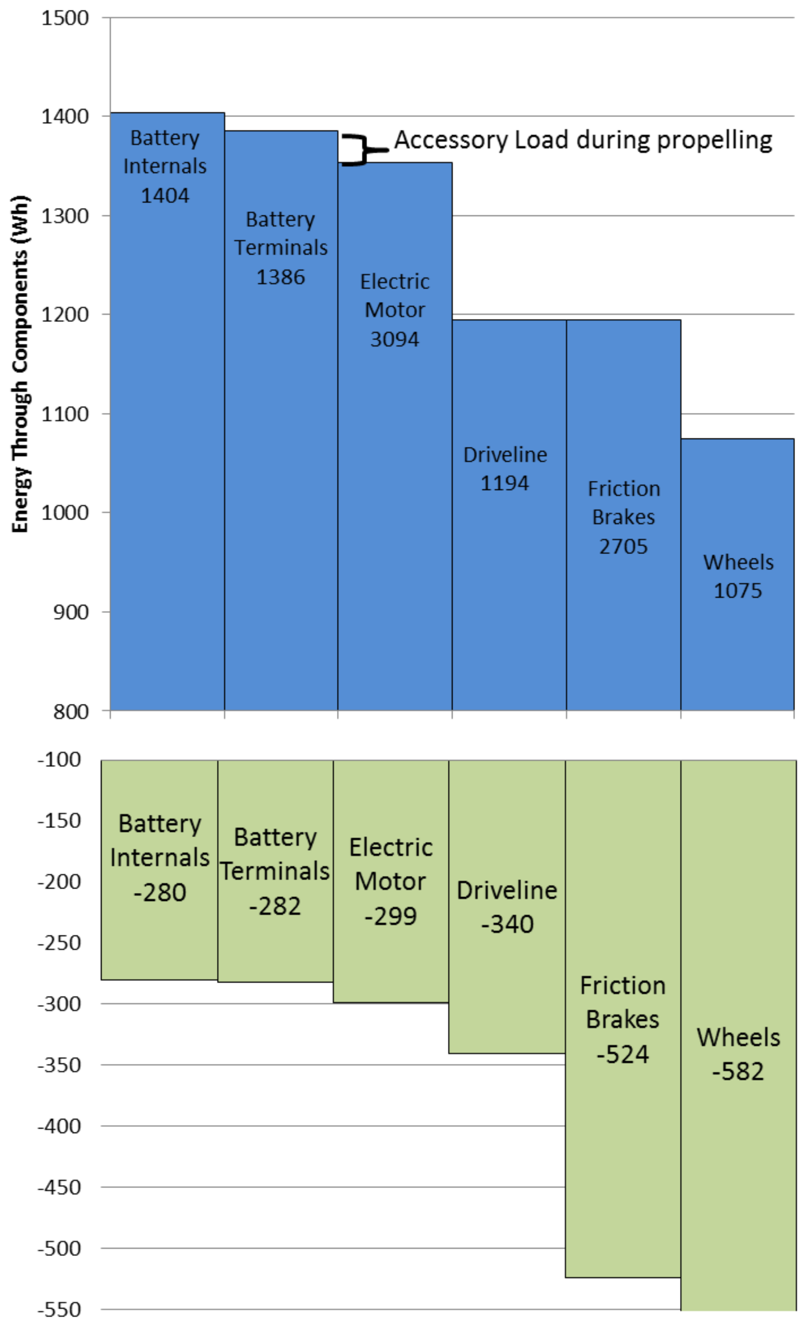

Figure 29: 505 Cycle Modeled Energy Flow Diagram

Table 25 shows general cycle data for the 505 cycle. There is a difference of 351Wh and a distance of .07 km between the test data collected from driving on the dynamometer and the federal certification cycle. Because of this difference in order to validate the model, another section of data (red) was run against the collected velocity information. The model does over predict the energy consumption for a '505' because it has higher braking average energy weighted efficiency for putting energy back into the RESS. The final DC Wh/km vary by less than 5 %. A table of all of the results complied for the '505' can be seen in Appendix A.

Table 25: 505 Cycle Data

	505 Test Data		505 Model		505 Cert
Cycle Time (s)	505		505		505
Cycle Distance (km)	5.85		5.85		5.78
Energy Use (Wh)	1108		1120		1057
Minimum Energy Consumption (Wh/km)	84		84		84
Energy Consumption (Wh/km)	189		191		183
Net Powertrain Efficiency: Eqn 35	0.44		0.44		0.46

4.2 HWFET Results

This section shows the same plots and tables as the section on the '505' but for the HWFET. Figure 30 shows the speed trace from the certification cycle, the model, and the test vehicle. The results for DC Wh/km on the HWFET will be used in conjunction with modeling results for the UDDS to determine a combined, unadjusted energy consumption and vehicle range as a pure EV.

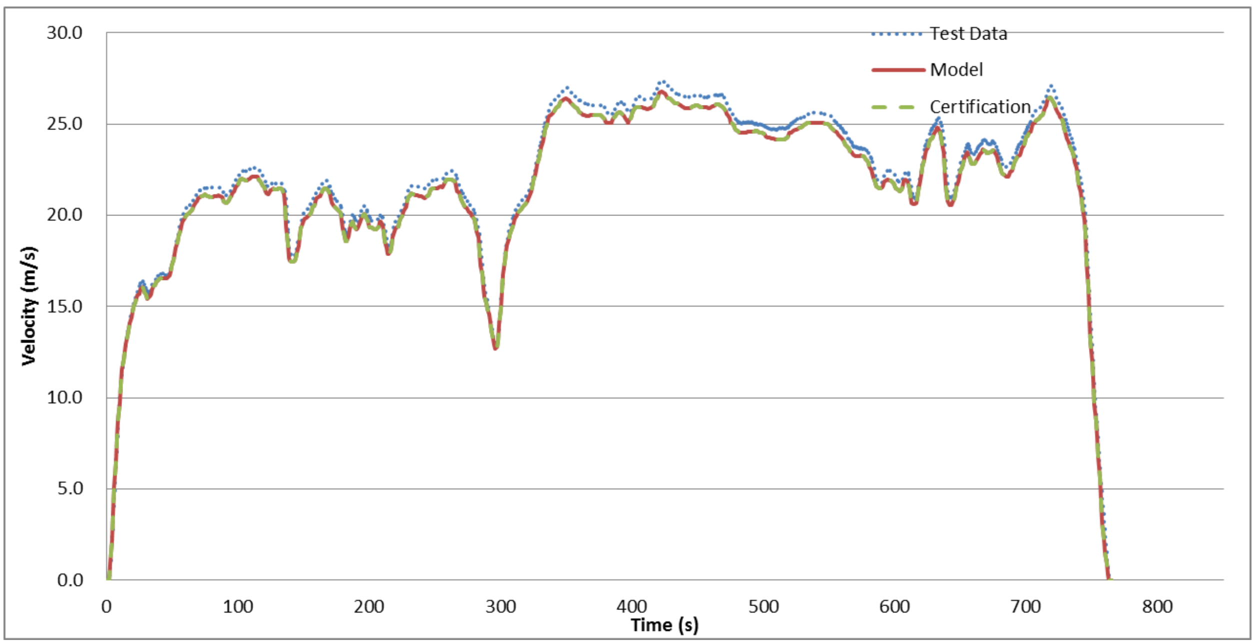

Figure 30: HWFET Velocity vs. Time

Figure 31 shows the acceleration for the certification cycle, the model, and vehicle which is calculated as a smoothed derivate from the speed trace as shown in Equation 31 previously. Note again that the acceleration or inertial term skews the data collected from the physical testing.

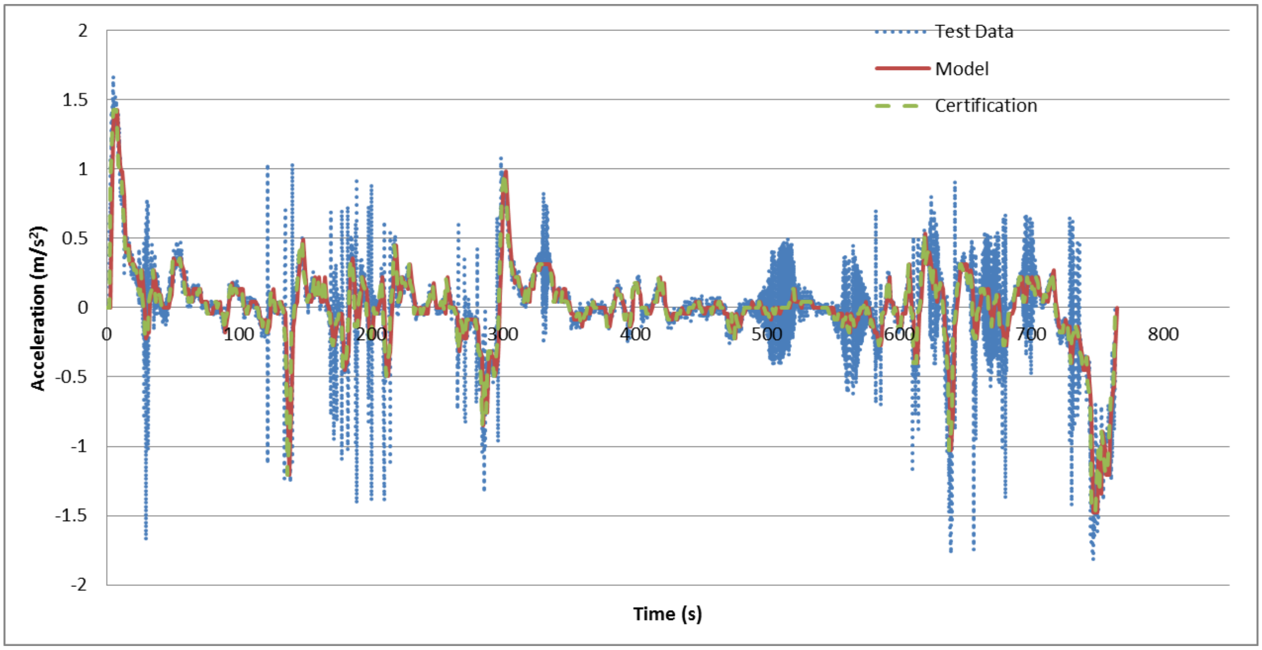

Figure 31: HWFET Acceleration vs. Time

The tractive power required at the wheels is shown in Figure 32. The mechanical output required from the electric motor to overcome braking and driveline losses in shown in Figure 33. Figure 34 is a plot of motor torque versus speed for the modeled performance case only. Finally the power at the terminals of the RESS is shown in Figure 35, which overcomes the losses in the electric motor and supplies the accessory load. While the model does take into account the energy lost in the internals of the RESS using a fixed internal resistance, the energy quoted here is simply the energy at the terminal since that value is what is easily measured and reported.

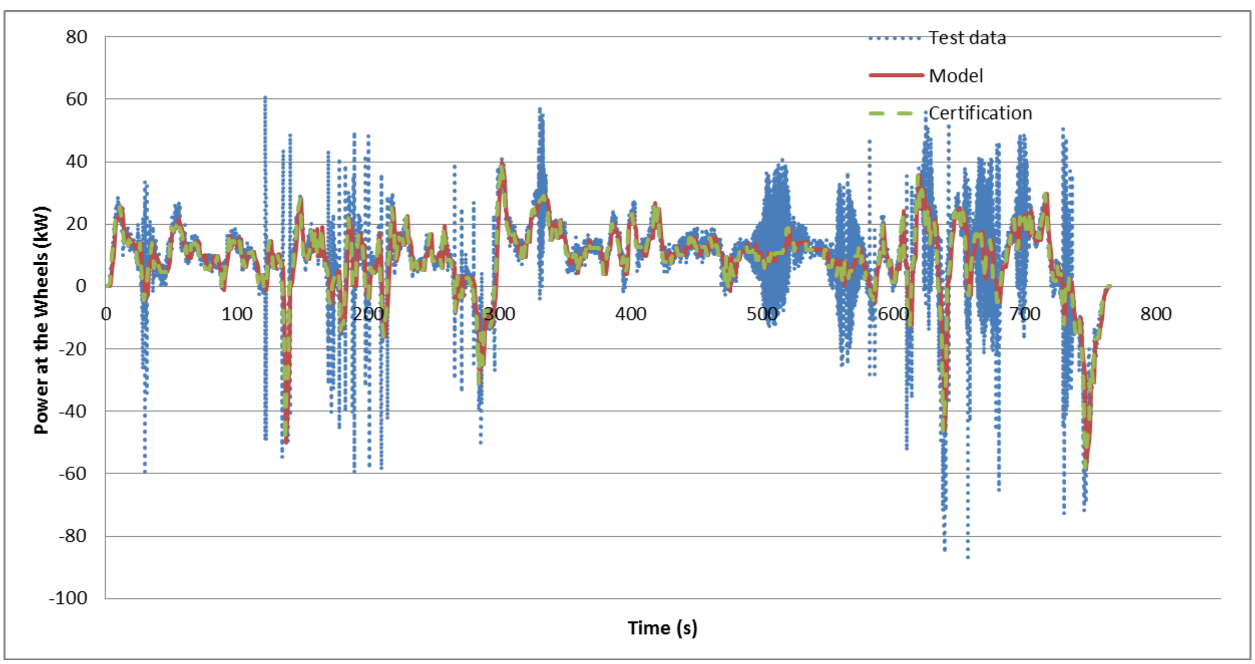

Figure 32: HWFET Tractive Power at the Wheels vs. Time

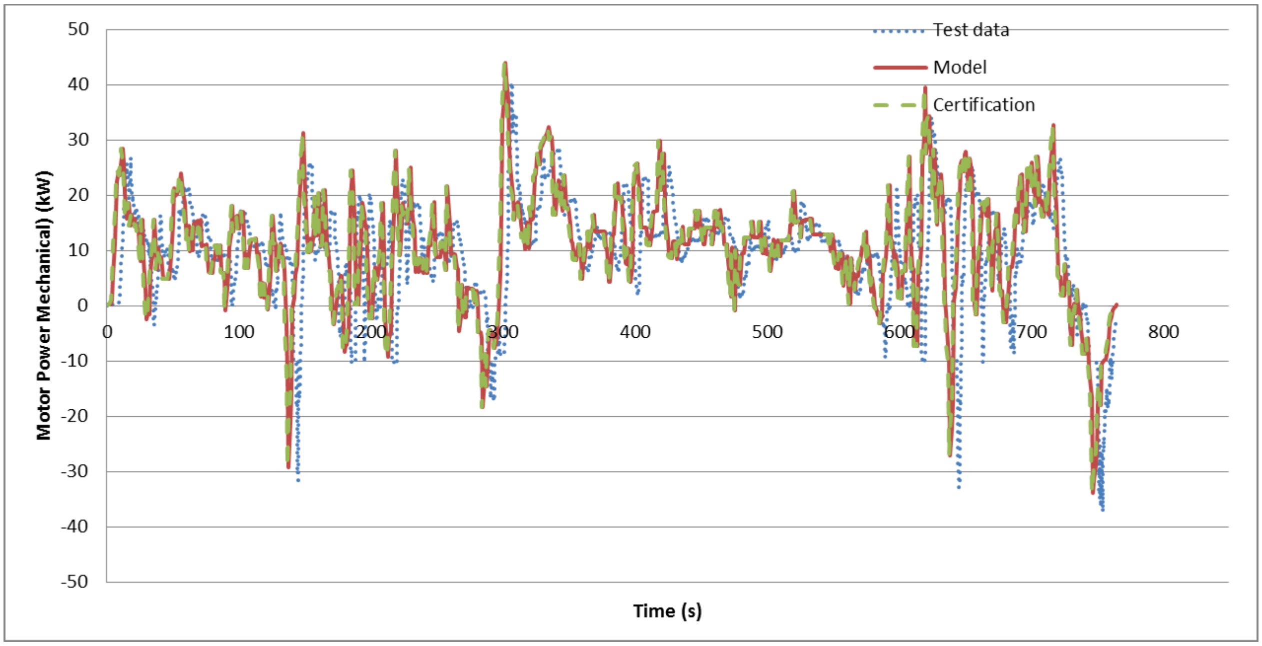

Figure 33: HWFET Motor Output (Mechanical) Power vs. Time

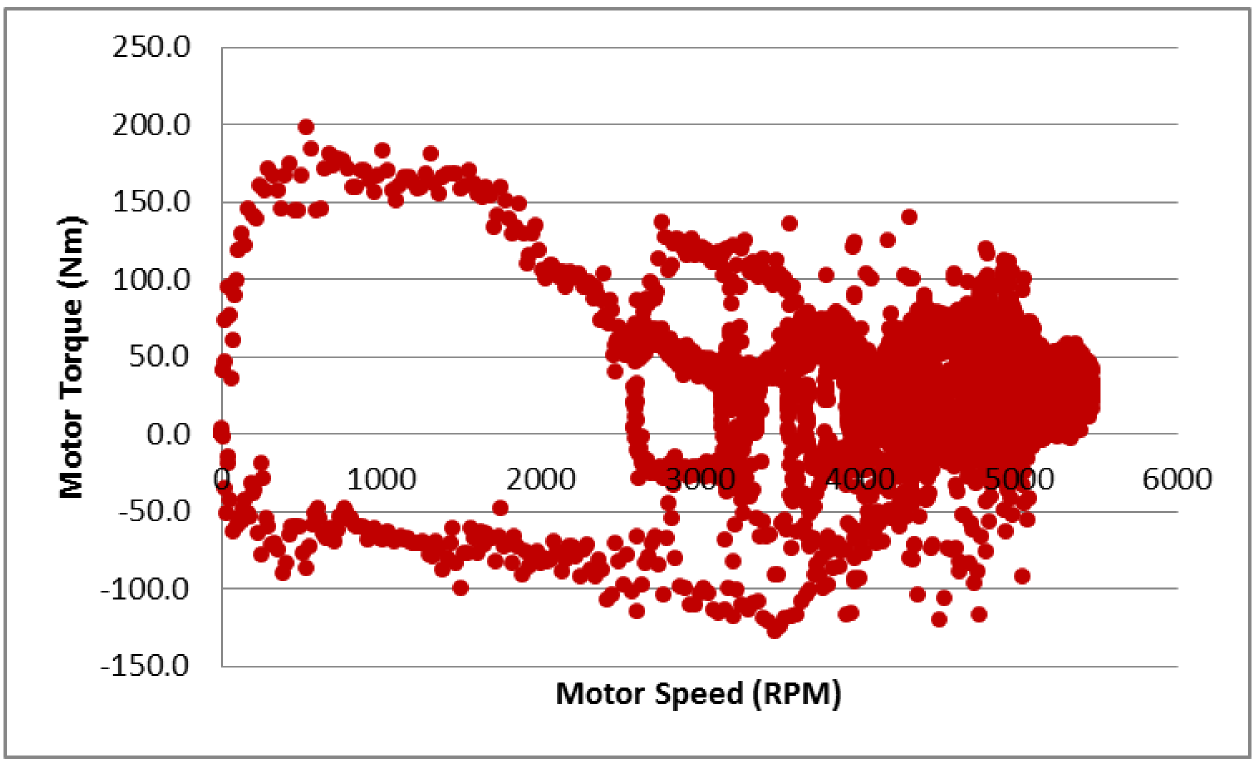

Figure 34: HWFET Cycle Modeled Motor Torque vs. Speed

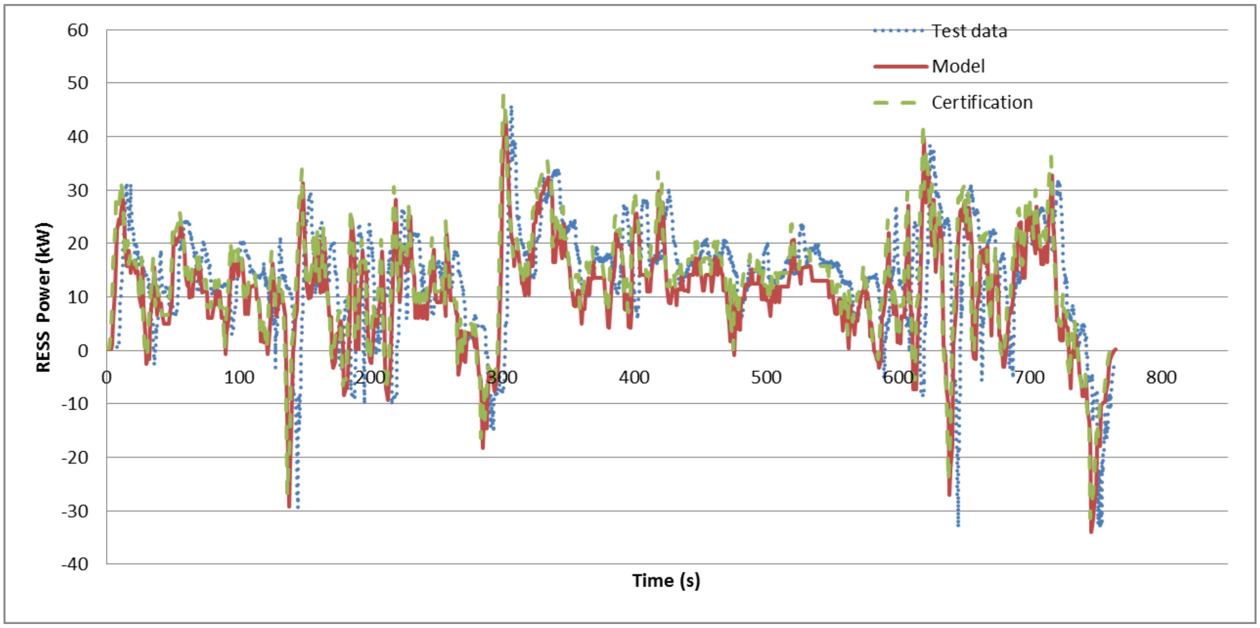

Figure 35: HWFET RESS Power vs. Time

The results of the HWFET model and test data can been seen in Table 26 through Table 28. This data in conjunction with the energy required to complete a UDDS cycle is used to calculate the combined, unadjusted energy consumption for an electric vehicle.

Table 26: HWFET Energy Consumption

	HWFET Test Data			HWFET Model			HWFET Cert		
Energy	Propel	Braking	Idle	Propel	Braking	Idle	Propel	Braking	Idle
Wheels (Wh)	2434.13	-481.08	-	2434.13	-481.08	-	2210.71	-351.78	-
Friction Brakes (Wh)	-	-432.98	-	-	-432.98	-	-	-316.60	-
Driveline (Wh)	2695.21	-231.88	-	2704.59	-281.43	-	2456.34	-205.79	-
Motor (Wh)	3030.67	-181.10	0.31	3094.19	-240.32	0.22	2838.36	-176.11	0.31
Battery Terminals (Wh)	3061.58	-177.43	0.48	3169.38	-225.57	0.62	2916.37	-164.17	0.90
Battery Internal (Wh)	3095.76	-174.06	0.48	3203.57	-223.86	0.62	2916.37	-164.17	0.90

Table 27: HWFET Energy Losses

	HWFET Test Data			HWFET Model			HWFET Cert		
Losses	Propel	Braking	Idle	Propel	Braking	Idle	Propel	Braking	Idle
Friction Brakes (Wh)	-	48.11	-	-	48.11	-	-	35.18	-
Driveline (Wh)	261.08	201.09	-	270.46	151.54	-	245.63	110.81	-
Motor (Wh)	335.46	50.79	0.31	464.79	55.86	0.22	382.02	29.68	0.31
Accessory Load (Wh)	30.90	3.66	0.17	75.19	14.75	0.40	78.02	11.94	0.59
Battery (Wh)	34.18	3.37	0.00	34.18	1.71	0.00	26.81	1.10	0.00

Table 28: HWFET Efficiencies

	HWFET Test Data		HWFET Model		HWFET Cert	
Efficiency	Propel	Braking	Propel	Braking	Propel	Braking
Regen: Eqn 16	-	0.90	-	0.90	-	0.90
Driveline: Eqn 15, 17	0.90	0.54	0.90	0.65	0.90	0.65
Motor: Eqn 18,19	0.89	0.78	0.85	0.80	0.87	0.86
Battery: Eqn 31	0.989	0.981	0.989	0.992	1.000	1.000
Total: Eqn 32, 33	0.80	0.37	0.77	0.47	0.76	0.47

The model and test data suggest that the VT_{REX} when driven on a cycle that mimics the UDDS and HWFET with no grade should have an electric energy consumption of 175 Wh/km. The current control strategy is to use 90 % SOC swing, which is 18 kWh at the terminals. This will lead to a total vehicle range as a pure EV of 107.5 km (67.5 miles). Figure 36 shows a visual representation of the energy flow through all of the components with losses.

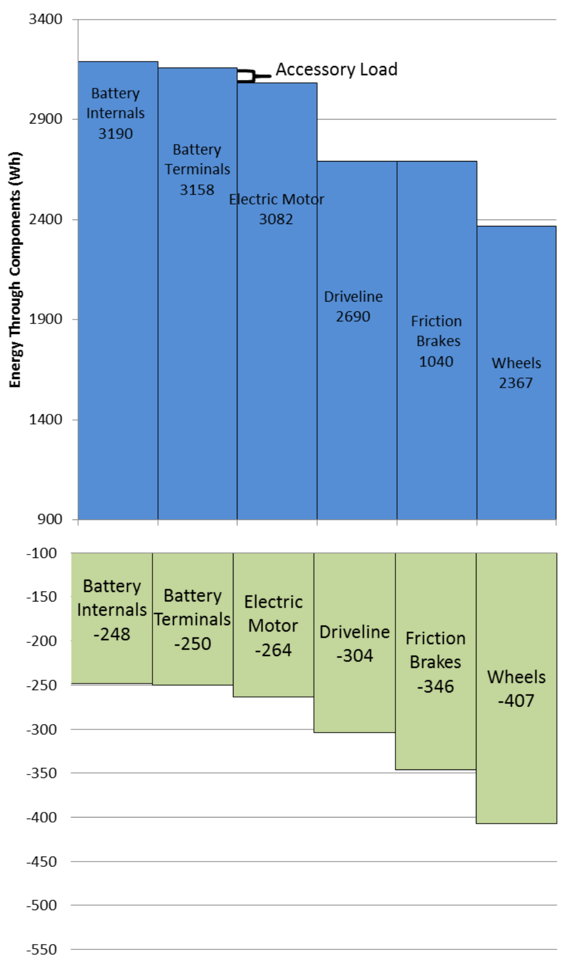

Figure 36: HWFET Cycle Modeled Energy Flow Diagram

Table 29 shows general cycle data for the HWFET cycle. There is a difference of 132 Wh and a distance of .35 km between the test data collected from driving on the dynamometer and the federal certification cycle. Because of this difference, in order to validate the model, another section of data (red) was run against the collected velocity information. The model does under predict the energy consumption for a HWFET because of the shorter distance and smaller accelerations experienced. The final battery electric consumption in DC Wh/km vary by less than 5 %. A table of all of the results complied for the HWFET can be seen in Appendix B.

Table 29: HWFET Cycle Data

	HWFET Test Data	HWFET Model	HWFET Cert
Cycle Time (s)	765	765	765
Cycle Distance (km)	16.86	16.86	16.51
Energy Use (Wh)	2885	2944	2753
Minimum Energy Consumption (Wh/km)	116	116	113
Energy Consumption (Wh/km)	171.1	174.7	166.8
Net Powertrain Efficiency: Eqn 35	0.68	0.66	0.68

4.3 Full Depleting UDDS Test

While at EPA, a test was performed by the organizers and testing staff from EPA was a full depletion test of the electric vehicle mode of the VT_{REX}. Shown below in Figure 37 is a plot of vehicle speed versus integrated amp hours for each UDDS cycle. The modeled data for a UDDS cycle predicts an integrated Amp-Hr use of 5.3 DC Amp-Hr, which is just slightly less than the measured test data collected. The vehicle was able to start the 10^{th} UDDS, but failed to compete the cycle because of a control software glitch. The glitch in messaging has been fixed, but the test was not able to be repeated. The vehicle used 92 % of the energy in the pack and was able to go 71 miles as a pure EV on a 2 wheel drive dynamometer. One thing to note about this case is that between run 1 and 2 the dynamometer driver requested that the commanded regen fraction be increased to allow the vehicle to meet the trace, as the front friction brakes were not able to assist in vehicle deceleration as the front axle was locked out. The vehicle range of 71 miles is slightly less than the predicted UDDS only range of 73 miles for a 92 % SOC swing. Using the information collected for the UDDS of 157 DC Wh/km and a HWFET of 166 DC Wh/km a predicted range combined, unadjusted for a 95 % SOC swing is 73 miles. A summary of the UDDS and US06 modeling results can be seen in Appendix C.

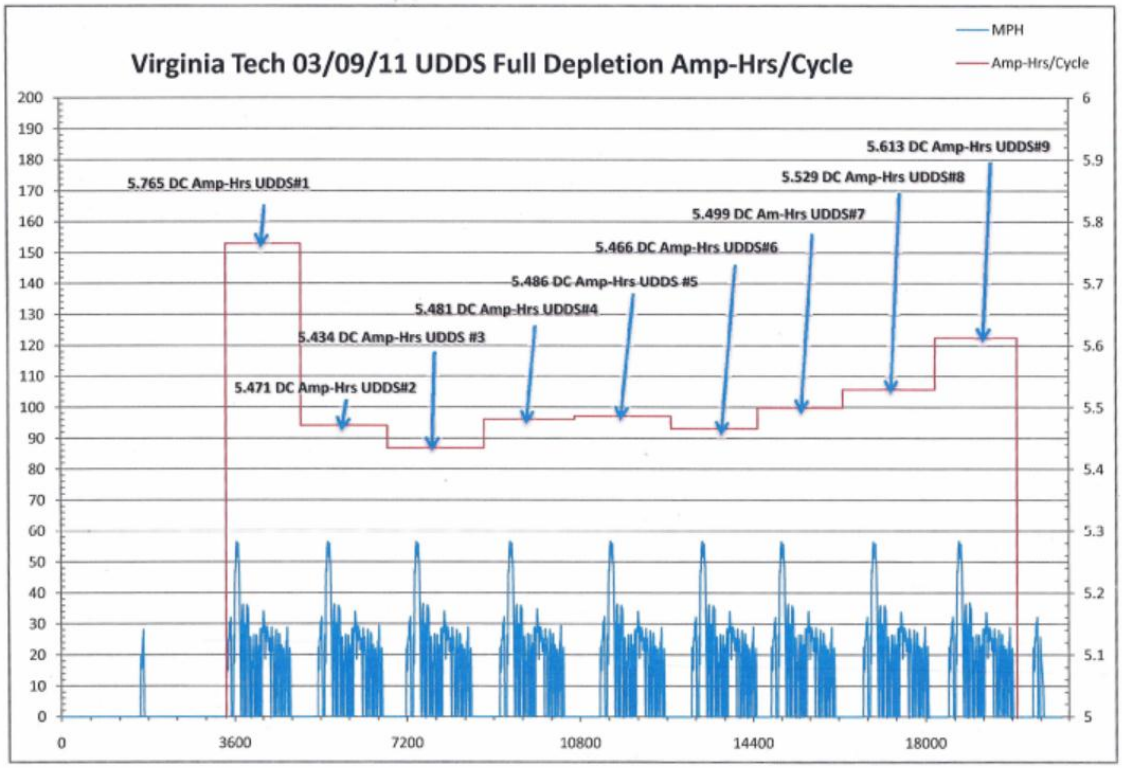

Figure 37: UDDS Full Depletion Amp-Hour vs. Time

4.4 Charging

After the full CD EV mode of the VT_{REX} was completed the vehicle was then pushed to near a wall outlet and charged off of a 240 VAC, 30 A circuit. The charger made by BRUSA, claims to be 92 % efficient, however in practice the energy weighted efficiency used in this model is 88 %, which is a direct correlation to the AC energy pulled from the grid and the energy that is stored in the RESS. The major difference is that the RESS does have losses, and that the DC/DC is powered during charging, thus creating a parasitic drain on the HV bus. The DC/DC must be enabled in order to power the RESS controller and other vehicle controllers, to monitor charging and coolant temperatures on board the vehicle. Using this information the vehicle has a combined, unadjusted energy consumption of 170 Wh DC/km, the AC energy required to drive the vehicle is 194 Wh AC/km. Table 30 shows a summary of the energy use and range on the useable energy of the RESS based on the model.

Table 30: Vehicle Range, DC, and AC Energy Consumption

	km	mi		Wh/km	Wh/mi		Wh/km	Wh/mi
Vehicle Range UDDS	115.5	71.8	UDDS DC	173	279	UDDS AC	197	317
Vehicle Range HWFET	120.1	74.6	HWFET DC	167	268	HWFET AC	190	305
Combined Range	117.5	73.0	Combined DC	170	274	Combined AC	194	312
Vehicle Range US06	72.5	45.0	US06 DC	276	445	US06 AC	314	505

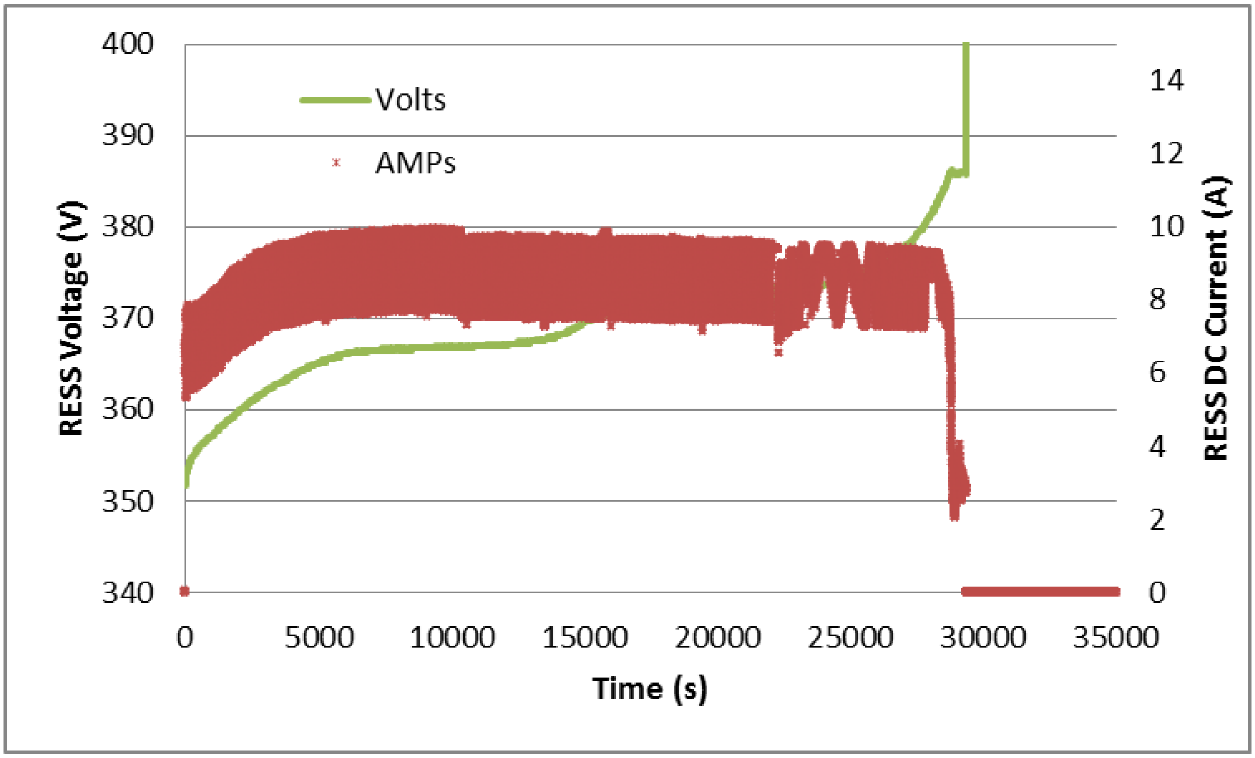

Figure 38: RESS Voltage (DC) and Current for a 0-100 SOC charge

4.5 Testing Conclusions

Using the data collected at EPA, the model developed was able to be further refined. The end result is being able to see the energy that is required at the wheels, where the losses are in the powertrain, and getting the right overall average drive cycle energy weighted efficiency terms. The importance of this energy term is that for propelling, that one single term can be used to calculate the energy required to propel the vehicle, if the tractive energy at the wheels is known. While the braking efficiency term, can be used to determine quickly how much of the braking energy available at the wheels will make it back into the RESS. These efficiency terms are drive cycle and vehicle dependent, and should be re-calculated when vehicle parameters change. However the numbers can be used to validate new possible improvements to decrease the energy consumption of the electric vehicle. This model, after validation predicts that the energy use for a combined cycle (UDDS and HWFET), unadjusted energy consumption to be 161 Wh DC/km and 183 Wh AC/km. Assuming an EV range that uses 95 % of the energy available in the RESS for propulsion the combined range prediction is 118 km (73 mi). A summary of all of the modeling parameters used can be found in Appendix D.

5. Applications

5.1 EcoCAR 2

While the majority of this work so far has been dedicated to the validation of this model for one particular vehicle platform, the VT_{REX}, the model can be used as a design tool. For instance this model could be used to validate initial design for an electric powertrain on a 2013 Chevy Malibu by future HEVT students participating in EcoCAR 2. The model will need to be further adjusted with testing, as the loading of torques and speed will be different leading to different drive cycle averaged energy weighted powertrain component terms. However this model when adjusted to the correct gliders properties will provide a useful test bed for validation of initial design concepts such as how big (mass or energy) of a RESS should be installed into the vehicle, and how does that effect the acceleration performance of the vehicle. Other design insights could be using the current motor efficiency equation, what gearing should be selected to ensure good acceleration performance to meet drive cycles like the US06, but to also have a good energy weighted motor and generator efficiency.

5.2 Utility Factor Fuel Consumption

This work has been focused on just the electric propulsion of the VT_{REX}. However the vehicle does have a range extending engine and transmission on board that currently is able to get 24 mpg on gasoline through on-road testing. The J1711 standard for utility factor weighting fuel economy was previously mentioned. Using the curve shown in Figure 39 as an approximation, a range of 73 miles give a Utility Factor of 0.78. Using Equation 42 this yields a Utility Factor Weighted Fuel Economy of 109 mpgge. This form of the Utility Factor weighting is only valid for a CD range when no liquid fuel is consumed.

$$UF_{mpggge} = \frac{Fuel\ Economy}{(1 - UF)} \tag{42}$$

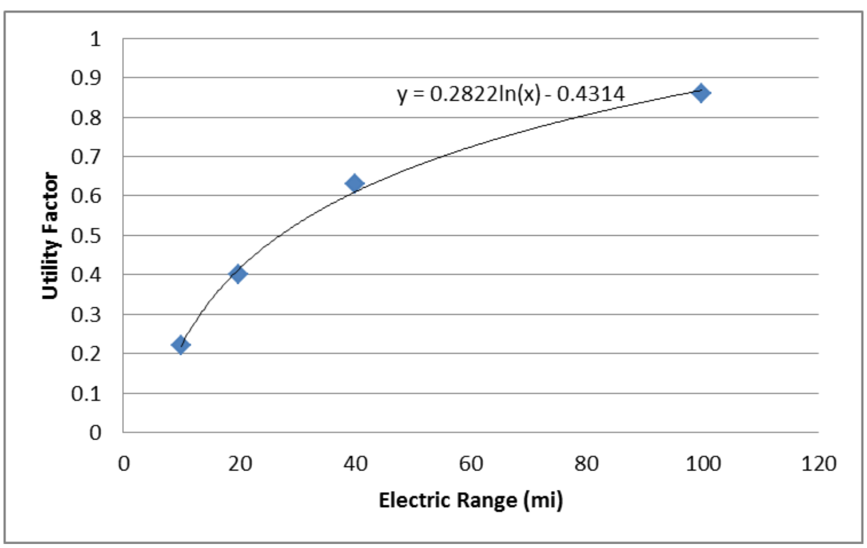

Figure 39: Utility Factor Curve

5.3 Future Work

A useful parameter that the model generates is the energy required at the terminals on the HV bus to meet the driver demand for a given cycle. This is extremely helpful in a series hybrid or a fuel cell vehicle powertrain as the result of operation is some amount of electrical energy output. Using the information gathered here, the future work suggested is for the inclusion of a range extending device that generates some amount of electricity on to the HV bus for use for propulsion through the main traction drive. Remembering that the goal of this work is to see quick and simple gains or losses in powertrain and braking drive cycle efficiencies so the control strategy developed should be keep to a minimum.

The results of the present analysis can be combined with Sovran's approach for conventional powertrains to estimate the energy consumption of more complex hybrid vehicles. The other cycles that Sovran included in his 2006 paper, should be included in this model, to see what interesting results and information can be learned.

In order for the results of this work to be truly valid, the data collection process needs to be improved. The speed signal from the dynamometer at EPA was very noisy, and caused an issue in calculating vehicle acceleration. When performing on-road tests in the vehicle in the future, the accuracy of the vehicle accelerometer should be verified, so that the model is based on good data. It would be helpful to also record elevation data on board the vehicle. While the impact of grade and slight elevation perturbations were covered in the modeling section, on-road vehicle data was never collected to verify the proposed impact on fuel economy. This could prove extremely helpful in predicting the E&EC utility factor weighted fuel economy for EcoCAR and EcoCAR2 if the track profile is given before competition.

While the inclusion of a coefficient of rolling resistance that scales with velocity was addressed and included in the model, no testing with a 'B' term was ever done. The future work should attempt to verify that the proposed C_{rr} and C_DA_f used in this report to match the testing done at EPA was a valid case. Looking into ways to include a 'B' term or a c_{rr_1} is also suggested. Bagoline used a different method to describe rolling resistance that could be a source of possible improvement for the road load calculations. All of this comes down to the ability to do more testing, more data manipulation, and more data analysis, so that the conclusions of this work in the prediction of range and energy consumption for this vehicle and for others becomes solid. In working with other universities that participated in EcoCAR, the inclusion of other vehicles that have similar powertrain characteristics could be looked into as well, or the direction of the work could led more to the validation of powertrain components for a 2013 Malibu for EcoCAR 2.

6. Conclusions

A lot of information can be gleaned from simply understanding the losses and component efficiencies for a vehicle powertrain. An Electric Vehicle (EV) can recover energy from kinetic energy back into the Rechargeable Energy Storage Subsystem (RESS) to use at a later time, thus decreasing the net energy needed from the RESS to complete the cycle. However the energy that flows into and out of the RESS and other components vary from just the net energy needed at the wheels for propulsion. By making sure to track the losses in each direction: propelling and braking, and remembering to take into account the idle and charge states, the vehicle grid energy or fuel energy consumption can be characterized. The methods developed within this thesis are a blend of theory, data collection in a controlled environment, and on-road testing.

The goal of this work was to predict the range of the Virginia Tech Range Extended Crossover (VT_{REX}) on standard EPA drive cycles. At the United States Environmental Protection Agency's National Vehicle and Fuels Emissions Laboratory in Ann Arbor, Michigan, the Hybrid Electric Vehicle Team (HEVT) of Virginia Techs vehicle was put to the test. The hard work of the team over 3 years paid off in that the vehicle was able to drive almost 72 miles as a pure EV on the Urban Dynamometer Driving Schedule (City). The model developed within this thesis, using the adjusted vehicle parameters was able to predict not only the range but also the energy flow and losses at each component. Unique to this work is that the energy flows for propelling, braking and idle were kept separate. This allowed for different energy weighted drive cycle averaged efficiencies depending on if the component was propelling of braking. For the RESS this did not seem to have much of an effect as the efficiency was generally around 99 %. However the driveline modeled shows a propel efficiency of almost 90 % but a braking efficiency of 65 %. All of this was used to calculate the energy required to complete several standard test cycles in the UDDS and the Highway Fuel Economy Test (HWFET) which together represent an unadjusted combined energy consumption of 161 Wh DC/km (at the battery terminals) and 183 Wh AC/km (energy from the electric grid). In addition to defining efficiencies for the propelling and braking state, a calculation for the net powertrain and braking efficiency was defined. This is the amount of energy required to complete the cycle that actually makes it way to overcome the tractive energy requirement at the wheels.

As a design tool, this approach and analysis is helpful for component selection and "what if" scenarios. Very quickly, the impact can be seen by changing the average motor efficiency, for example, and its effect on the overall vehicle energy flow. By understanding the components and what goes on within the energy flow, characterizing the vehicle energy consumption becomes a much easier task, because now it is known where all of the energy losses are going, not just the net energy. This simplified design model has been applied to the current vehicle design, the VT_{REX}, and future vehicles built and developed by HEVT so as to accurately predict the energy use during on-road testing.

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Appendix A: ‘505’ Test Results

	505 Test Data				505 Model				505 Cert		
Cycle Time (s)	505				505				505		
Cycle Distance (km)	5.85				5.85				5.78		
Energy Use (Wh)	1108				1147				1080		
Energy Consumption (Wh/km)	189				196				187		
Energy	Propel	Braking	Idle		Propel	Braking	Idle		Propel	Braking	Idle
Wheels (Wh)	1004.39	-509.32	-		1004.39	-509.32	-		915.70	-427.41	-
Friction Brakes (Wh)	-	-432.93	-		-	-432.93	-		-	-363.30	-
Driveline (Wh)	1040.42	-248.02	-		1040.42	-245.13	-		1040.42	-205.71	-
Motor (Wh)	1210.44	-164.35	2.95		1293.04	-211.42	5.51		1190.56	-176.53	5.94
Battery Terminals (Wh)	1242.91	-147.97	13.18		1325.82	-194.89	15.83		1223.80	-161.15	17.06
Battery Internal (Wh)	1255.46	-146.49	13.18		1341.70	-194.07	15.83		1237.62	-160.51	17.06
Losses	Propel	Braking	Idle		Propel	Braking	Idle		Propel	Braking	Idle
Friction Brakes (Wh)	-	76.40	-		-	76.40	-		-	64.11	-
Driveline (Wh)	36.03	184.91	-		36.03	187.79	-		124.72	157.59	-
Motor (Wh)	170.02	83.67	2.95		252.62	33.71	5.51		150.14	29.18	5.94
Accessory Load (Wh)	32.47	16.38	10.23		32.78	16.53	10.32		33.24	15.38	11.12
Battery (Wh)	12.55	1.48	0.00		15.88	0.83	0.00		13.82	0.64	0.00
Efficiency	Propel	Braking			Propel	Braking			Propel	Braking	
Regen	-	0.85			-	0.85			-	0.85	
Driveline	0.97	0.57			0.97	0.57			0.88	0.57	
Motor	0.86	0.66			0.80	0.86			0.87	0.86	
Battery	0.990	0.990			0.988	0.996			0.989	0.996	
Total	0.81	0.29			0.76	0.38			0.75	0.38	

Appendix B: HWFET Test Results

	HWFET Test Data				HWFET Model				HWFET Cert		
Cycle Time (s)	765				765				765		
Cycle Distance (km)	16.86				16.86				16.51		
Energy Use (Wh)	2885				2908				2739		
Energy Consumption (Wh/km)	171.1				172.5				165.9		
Energy	Propel	Braking	Idle		Propel	Braking	Idle		Propel	Braking	Idle
Wheels (Wh)	2367.42	-406.91	-		2367.42	-406.91	-		2164.43	-298.80	-
Friction Brakes (Wh)	-	-345.88	-		-	-345.88	-		-	-253.98	-
Driveline (Wh)	2360.64	-231.88	-		2689.86	-304.41	-		2459.22	-223.53	-
Motor (Wh)	3030.39	-180.81	0.31		3081.51	-263.96	0.22		2841.93	-194.10	0.31
Battery Terminals (Wh)	3061.58	-177.43	0.48		3157.74	-250.25	0.62		2920.66	-182.87	0.90
Battery Internal (Wh)	3094.32	-175.26	0.48		3190.48	-248.08	0.62		2920.66	-182.87	0.90
Losses	Propel	Braking	Idle		Propel	Braking	Idle		Propel	Braking	Idle
Friction Brakes (Wh)	-	61.04	-		-	61.04	-		-	44.82	-
Driveline (Wh)	-6.78	113.99	-		322.44	41.46	-		294.80	30.45	-
Motor (Wh)	669.75	51.08	0.31		467.88	54.16	0.22		382.71	29.43	0.31
Accessory Load (Wh)	31.19	3.37	0.17		76.23	13.71	0.40		78.73	11.23	0.59
Battery (Wh)	32.74	2.18	0.00		32.74	2.18	0.00		26.05	1.41	0.00
Efficiency	Propel	Braking			Propel	Braking			Propel	Braking	
Regen	-	0.85			-	0.85			-	0.85	
Driveline	1.00	0.67			0.88	0.88			0.88	0.88	
Motor	0.78	0.78			0.85	0.82			0.87	0.87	
Battery	0.989	0.988			0.990	0.991			1.000	1.000	
Total	0.77	0.44			0.75	0.62			0.74	0.61	

Appendix C: UDDS and US06 Modeling Results

	UDDS				US06		
Cycle Time (s)	1372				596		
Cycle Distance (km)	12.0				12.9		
Energy Use (Wh)	1887				3276		
Energy Consumption (Wh/km)	157.3				254.2		
Energy	Propel	Braking	Idle		Propel	Braking	Idle
Wheels (Wh)	1773.72	-969.02	-		2973.78	-1015.99	-
Friction Brakes (Wh)	-	-823.67	-		-	-863.59	-
Driveline (Wh)	2015.30	-724.93	-		3378.82	-760.07	-
Motor (Wh)	2335.31	-626.09	15.31		3869.88	-666.79	2.25
Battery Terminals (Wh)	2423.09	-580.60	44.14		3918.37	-648.93	6.51
Battery Internal (Wh)	2444.78	-577.50	44.14		4012.59	-641.07	6.51
Losses	Propel	Braking	Idle		Propel	Braking	Idle
Friction Brakes (Wh)	-	145.35	-		-	152.40	-
Driveline (Wh)	241.58	98.74	-		405.03	103.52	-
Motor (Wh)	320.01	98.84	-		491.07	93.28	-
Accessory Load (Wh)	87.78	45.48	28.83		48.48	17.86	4.26
Battery (Wh)	21.69	3.10	0.01		94.22	7.86	0.00
Efficiency	Propel	Braking			Propel	Braking	
Regen	-	0.85			-	0.85	
Driveline	0.88	0.88			0.88	0.88	
Motor	0.86	0.86			0.87	0.88	
Battery	0.991	0.995			0.977	0.988	
Total	0.73	0.60			0.76	0.64	

Appendix D: Model Parameters for EPA Testing

Inputs		Calculated Parameters	
Test Mass (kg)	2270	Peak Motor Torque (N-m)	300
Inertial Mass Factor	1.04	Peak Motor Power (kW)	125.0
C_d	0.348	0-60 mph (s)	12.7
A_f (m^2)	2.64	50-70 mph (s)	5.9
C_rr	0.0054	N/v (rpm/(m/s)	200.0
Tire Rolling Radius (m)	0.353		
Density of Air (kg/m^3)	1.2		
Gravity (m/s^2)	9.81	Vehicle Range UDDS (km)	115.5
Vehicle Gearing	7.17	Vehicle Range HWFET (km)	120.1
Drivetrain Propel Efficiency	0.9	Combined Range (km)	117.5
Driveline Braking Efficiency	0.65	Vehicle Range US06 (km)	72.5
Motor efficiency	Eqn 20/21		
Grade (%)	0.00%	UDDS Cycle Distance (km)	12.0
Weight dist Front	0.54	HWFET Cycle Distance (km)	16.5
Regen Fraction	0.9	US06 Cycle Distance (km)	12.9
Accessory Load (W)	425		
Iw (kg m^2)	1.8	Utility Factor	0.78
Charging Efficiency	0.88	CAFE Combined FE (mpgge)	24
Motor Idle Power Draw (kW)	0.225	Utility Factory Weighted FE (mpgge)	109
Battery			
Open Circuit Voltage (V)	360	Internal Resistance	0.06
State of Charge	1	Energy Capacity (kWh)	20.0
Battery Mass (kg)	267	Useable Energy Capacity (kWh)	20.0