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System Level Modeling and Simulation of Hybrid Vehicles

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Abstract

System Level Modeling and Simulation of Hybrid Vehicles

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Development and validation of a system level power loss model of different Hybrid Vehicle architectures for performance and energy consumption comparisons. This will include understating the primary losses involved in propulsion of a vehicle, modeling components, and post processing of the gathered results.

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I would like to express my gratitude to my advisor, Professor Brian C. Fabien, for his guidance in both academic and personal life. His dedication to students is an excellent example and inspiration to me. I also wish to thank the UW EcoCAR Team (2013-2015) who have been with me through thick and thin, and made my work as a graduate student fun. Finally, I would like to thank my family for their support in every challenge I take on.

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TABLE OF ACRONYMS

Acronym	Meaning
AWD	All Wheel Drive
CD	Charge Depleting
CS	Charge Sustaining
GREET	Greenhouse Gas, Regulated Emissions and Energy Use in Transportation
GUI	Graphical User Interface
IVM	Initial Vehicle Movement
KMPH	Kilometer per Hour
MPH	Miles per Hour
PEU	Plug-in Hybrid Electric Vehicle
RPM	Rounds per Minute
SOC	State of Charge
TV	Torque Vectored
UF	Utility Factor

INTRODUCTION

System level modeling of a vehicle is a key step in vehicle design and development process. System level modeling for vehicle design is a cost cutting technique used by all leading companies in the automotive sector. Modeling and simulating proposed vehicle architecture to test its results against the design targets, will serve as an initial test to validate the vehicle. This will help justify the purchase of all the expensive powertrain components. Also, more than one vehicle architecture can be compared with one another to decide which fits the design targets the best. This article discusses power-loss modeling technique, and compares four vehicle architectures against a design target. Even if the all the vehicle meet the design targets, there are a lot of building considerations, and tradeoffs between energy consumption and performance that has to addressed.

POWER LOSS MODELING

Power-loss modeling is based off of the law of conservation of energy. Power-loss modeling of a system involves subtracting energy losses in the system from the primary energy source to give the net energy used to do useful work. In the case of a vehicle, the primary energy source is fossil fuel and electricity. The losses will include the energy used to overcome the road load and component efficiency losses.

Powertrain Components Efficiencies

Powertrain components have different efficiencies at which it operates. It is important to make sure to subtract all the power lost in each powertrain component. The powertrain components do not have the same efficiency at all there operating points. Efficiencies of some components like torque couplers and transmissions do not vary much, and hence can be considered to have one efficiency point.

Components with more than one efficiency point

The main two components in that have variable efficiencies is the Motor and Engine. The efficiency loss in these components are found based on the components operating point. Generally, the efficiency is pulled off a 3-demension graph with speed, torque and efficiency as the axes. Eg. **Figure 1** shows the efficiency map of the EMRAX 268 motor. An example of a component model in Matlab/Simulink can be found in the **Appendix** as **Component modelling Example.**

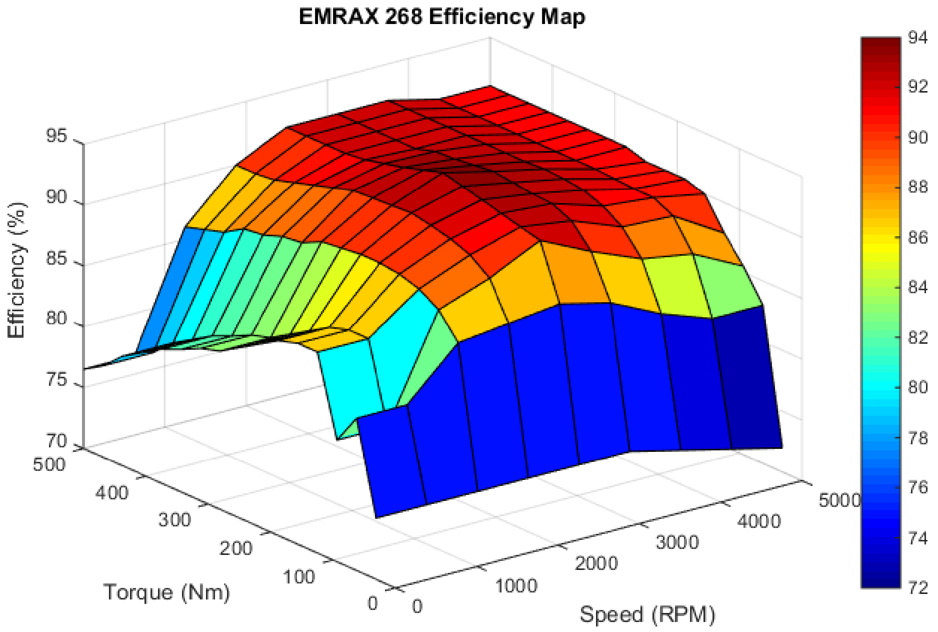


Figure 1 : EMRAX 268 Efficiency map

Road Load Equation (Vehicle Glider Model)

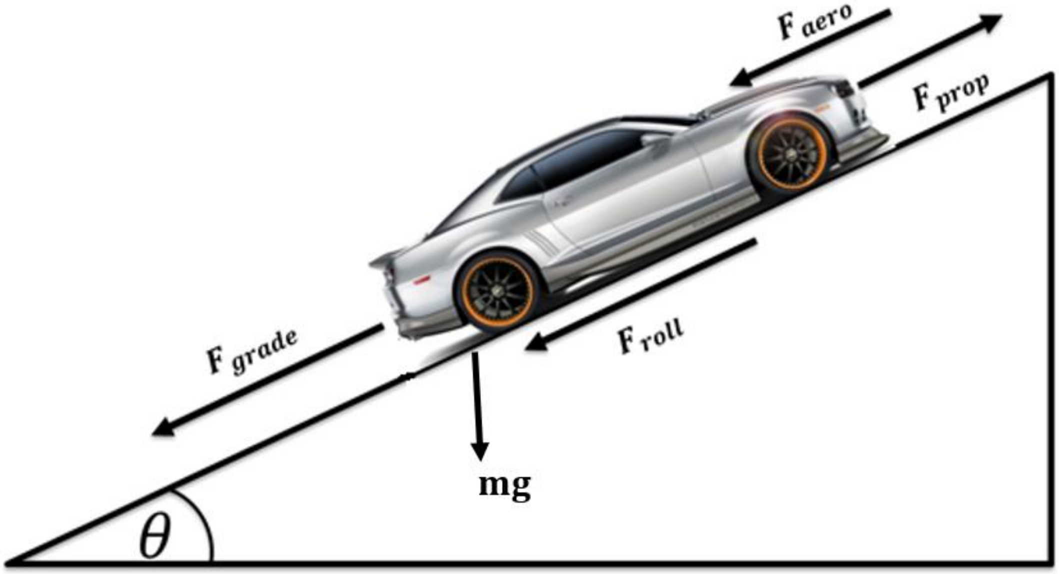


Figure 2 : Vehicle Free Body Diagram

The Road Load Equation includes the losses incurred overcoming Friction, Road gradient, and Aerodynamic drag post power conversion from the primary energy source to useable tractive energy. **Equation 1** shows the net force from the powertrain used for vehicle propulsion. **Figure 3** shows a Sankey diagram of the distribution of the Road Load Forces.

Equation 1 : Net Force available for Propulsion

$$\boldsymbol{F_{prop} = F_{tr} - F_{grade} - F_{roll} - F_{aero}}$$

Where F_{prop} – Propulsion Force, F_{tr} – Tractive Force, F_{grade} – Gradient Resistive Force, F_{roll} –Rolling resistance, F_{aero} - Aerodynamic drag.

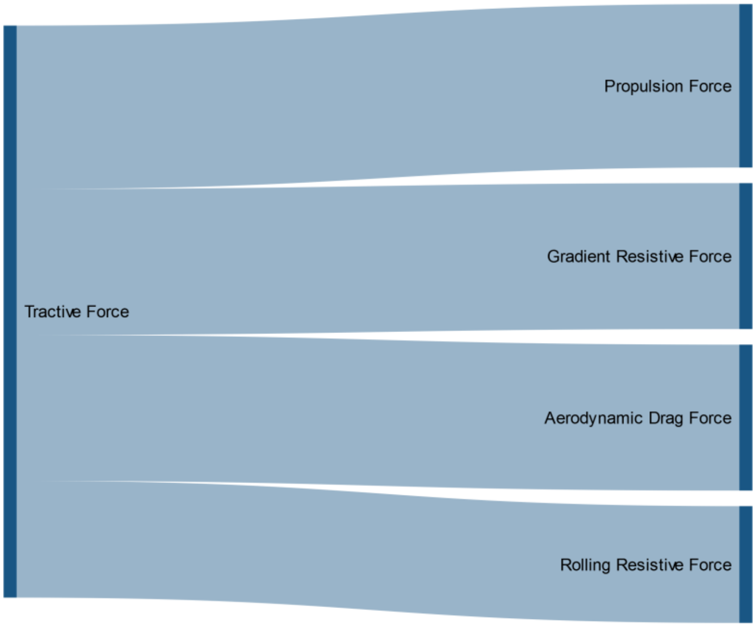


Figure 3 : Sankey Diagram of the Road Load Forces

Gradient Resistive Force

The Gradient Resistive force is the force that is needed to overcome the weight of the vehicle going up a grade. This force effects the road load only if the vehicle is on a slope. The Grade force will work against or for the vehicle propulsion depending on whether the vehicle is going uphill or downhill.

Equation 2 : Grade Resistive Force

$$\boldsymbol{F_{grade} = (direction) * m * g * \sin\theta}$$

Where m – mass of the vehicle, g – acceleration due to gravity, θ – grade angle.

Rolling Resistive Force

The Rolling Resistive Force is the force needed to overcome the longitudinal rolling friction of the wheel. The basic equation that governs the rolling resistance is given in Equation 3.

Equation 3 : Rolling Resistive Force

$$\boldsymbol{F_{roll} = m * g * C_{rr}}$$

Where the m – mass of the vehicle, g – acceleration due to gravity, C_{rr} – coefficient of rolling friction.

The coefficient of rolling friction is calculated as third-order polynomial of speed. The coefficients vary depending on the road surface conditions.

Aerodynamic Drag Force

The Aerodynamic Drag Force is the resistive force due to the oncoming air. The governing equation is shown in Equation 4.

Equation 4 : Aerodynamic Drag Force

$$F_{aero} = \frac{1}{2} * C_{da} * A * \rho * v^2$$

Where C_{da} – Coefficient of Drag, A – Frontal Area of the vehicle, ρ – Density of Air, v – vehicle velocity.

Aerodynamics of a vehicle play a key role in vehicle performance and energy consumption. Vehicles designed for uplift will reduce the net weight of the vehicle. This will in turn affect **Equation 2** and **Equation 3** reducing the energy consumption. However this will make the vehicle at high speeds. [1]

An example of modelling the vehicle glider model in Matlab/Simulink can be found in the Appendix as Vehicle Glider Model .

ARCHITECTURES UNDER STUDY

Vehicle Architectures

Torque Vector Architecture: Series -TV-A

The first vehicle uses the Torque Vector Architecture, powered by two Enstroj EMRAX 268 traction motors, one on each rear wheel, coupled to custom gear boxes, and controlled using the Unitek Bamocar-D3 700/400 motor controller. Electrical energy comes from an A123 7x15s3p Energy Storage System (ESS) and an electrical generator consisting of a E85 converted Honda VFR 800 engine coupled to a Bosch SMG 180 Gen 1 motor and Bosch INVCON Gen

2.3 motor controller. The only sponsored component are the A123 7x15s3p ESS, the Bosch SMG 180 and INVCON controller. The powertrain diagram is found on **Figure 4 : Series -TV-A Powertrain** Diagram**.**

Torque Vector Architecture: Series -TV-B

The third vehicle uses the Torque Vector Architecture, incorporating two Enstroj EMRAX 268 traction motors. Each motor powers a single rear wheel through custom gear boxes and is controlled using a Unitek Bamocar-D3 700/400 motor controller. Electrical energy comes from an A123 7x15s3p ESS and an electric generated consisting of a converted Honda VFR 800 engine coupled to an Enstroj EMRAX 228 motor and RMS PM100DX motor controller. The only sponsored component is the A123 7x15s3p ESS. The powertrain diagram is found on **Figure 5 : Series -TV-B Powertrain Diagram**. The difference between this vehicle and the first is the use of a non-competition sponsored motor and motor controller coupled to the E85 engine.

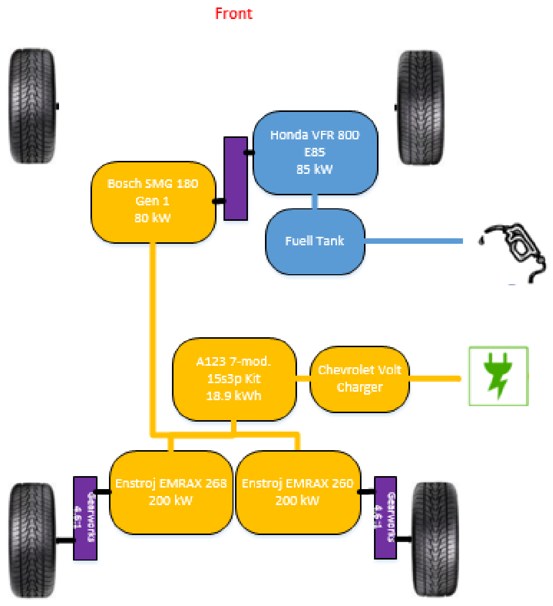


Figure 4 : Series -TV-A Powertrain Diagram

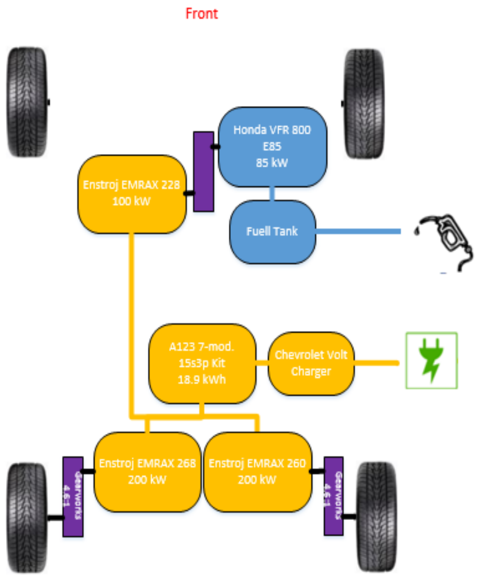


Figure 5 : Series -TV-B Powertrain Diagram

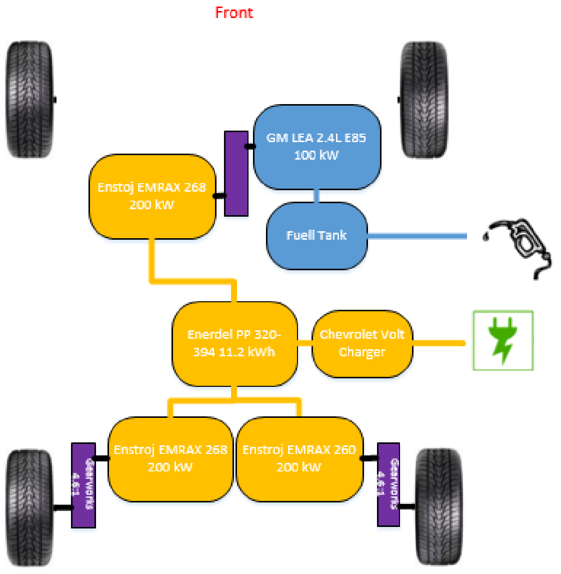


Figure 6 : Series-TV-C Powertrain Diagram

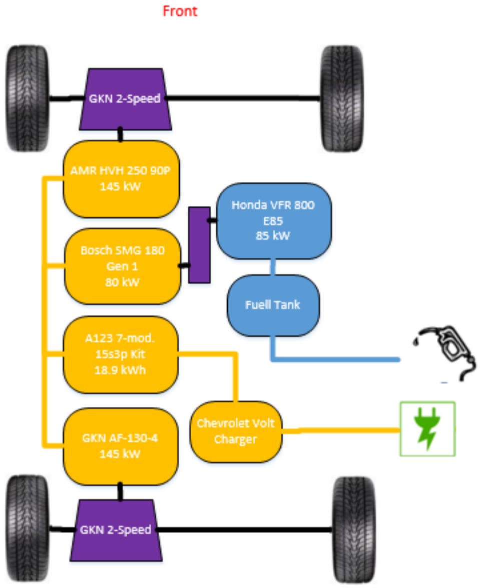


Figure 7 : Series-AWD Powertrain Diagram

Torque Vector Architecture: Series -TV-C

The final vehicle is a Torque Vectored Architecture, powered by two Enstroj EMRAX 268 traction motors. Each motor powers a single rear wheel through custom gear boxes and is controlled using a Unitek Bamocar-D3 700/400 motor controller.

Electrical energy comes from Enerdel PP 320-394 ESS and an electric generator consisting of a E85 converted GM 2.4L LEA engine coupled to a AMR HVH250-90P electric motor and Rinehart PM150DX motor controller. The only sponsored component are the Enerdel PP 320-394 ESS and GM 2.4L LEA. The powertrain diagram is found on **Figure 6 : Series-TV-C Powertrain Diagram**.

Ryan 2x2 Architecture: Series – AWD

The second vehicle used the Ryan 2x2 Architecture incorporating two GKN 2-Speed Electric Gearboxes, one on each axel. The forward axel is powered by an AMR HVH250 and RMS PM150DX motor controller and the rear axle is powered by a GKN AF-130-4 and RMS PM150DX motor controller. Electrical energy comes from an A123 7x15s3p ESS and an electrical generator consisting of a E85 converted Honda VFR 800 engine coupled to a Bosch SMG 180 Gen 1 motor and Bosch INVCON Gen 2.3 motor controller. The only sponsored component are the A123 7x15s3p ESS, two GKN 2-Speed

Gearboxes, the Bosch SMG 180, and INVCON controller. The powertrain diagram is found on **Figure 7 : Series-AWD Powertrain Diagram**.

Powertrain Components Specifications

Table 1 : Powertrain Components

	Component Description	Manufacturer and Model	Performance Specifications
Motors	Series -TV (A/B), Traction Motor	Enstroj EMRAX 268 'Medium Voltage Liquid Cooled'	200 kW Peak
	Series - TV - B Generator Motor	Enstroj EMRAX 228 'Medium Voltage Liquid Cooled'	100 kW Peak
	Series AWD Rear Traction Motor	GKN AF-130	140 kW Peak
	Series AWD Forward Traction Motor, Series TV Generator Motor	AMR HVH250	145 kW Peak
	Series - TV - A, Series - AWD Generator Motor	Bosch SMG 180 Gen 1	80 kW Peak
Motor Controllers	Generator Motor Controller	Bosch INVCON Gen 2.3	85 kW Peak
	Inverter for EMRAX 268	Unitek Bamocar D3 700-400	140 kW Peak
	Inverter for EMRAX 228	Rinehart PM100DX	100 kW Peak
	Inverter for AF-130 / HVH250 / EMRAX 268	Rinehart PM150DX	150 kW Peak
	Inverter for AF-130 / HVH250 / EMRAX 268	Rinehart PM250DX	250 kW Peak

Engines	Series TV E85 Engine	GM 2.4L LEA	136 kW peak, 233 Nm peak
	Series E85 Engine	Honda VFR 800 Engine	80 kW
Gearboxes	TV Gearboxes	Custom Boxes	Gear Ratio: 4.2
	AWD Series Gearboxes	GKN 2-Speed	Gear Ratio: 11.38/5.85
ESS	Series -TV-(A/B), Series -AWD ESS	A123 7x15s3p ESS	18.9 kWh, 600 Apm Peak, 340V nominal
	Series-TV-C ESS	Enerdel PP 320-394	11.2 kWh, 320 Amp Peak, 240-394 V

Weight Analysis and Weight Distribution

Weight Analysis of the vehicle plays a major role in determining the accuracy of the model. The Road load equation heavily relies on accurate calculation of the vehicle weight. Table 2 shows the weight estimation done for the four vehicles. It is assumed that the four vehicles are built on the same chassis. Extra weight is added as a margin of error.

Table 2 : Weight Analysis

Component	**SERIES - TV - A**	kg	**SERIES - TV - B**	kg	**SERIES – TV - C**	kg	**SERIES - AWD**	kg
Drive Motors	EMRAX 268	20.30	EMRAX 268	20.30	EMRAX 268	20.30	HVH 250-90P	45.80
	EMRAX 268	20.30	EMRAX 268	20.30	EMRAX 268	20.30	AF-130-4	30.50
Drive Motor Controller	Bamocar D3 700/400	8.55	Bamocar D3 700/400	8.55	Bamocar D3 700/400	8.55	PM150DX	10.70
	Bamocar D3 700/400	8.55	Bamocar D3 700/400	8.55	Bamocar D3 700/400	8.55	PM150DX	10.70

Gear Box	Custom Gearbox	15.00	Custom Gearbox	15.00	Custom Gearbox	15.00	2spd GKN	27.00
	Custom Gearbox	15.00	Custom Gearbox	15.00	Custom Gearbox	15.00	2spd GKN	27.00
Engine	VFR 800	68.00	VFR 800	68.00	GM 2.4L LEA	205.00	VFR 800	68.00
Gen Motor	SMG 180	32.00	EMRAX 228	12.30	HVH 250-90P	45.80	SMG 180	32.00
Gen Motor Controller	INVCON	7.00	PM100DX	7.50	PM150DX	10.70	INVCON	7.00
Charger	NLG513	6.30	NLG513	6.30	NLG513	6.30	NLG513	6.30
Pack	A123 7x15s3p	196.30	A123 7x15s3p	196.30	Enerdel PP-320-394	152.00	A123 7x15s3p	196.30
Fuel Weight	24.64	19.46	24.64	19.46	24.64	19.46	24.64	19.46
Fuel Tank	SERIES Tank	8.00	SERIES Tank	7.00	SPHEV Tank	7.00	SERIES Tank	8.00
Exhaust	Small E85 Engine	5.00	Small E85 Engine	5.00	Large E85 Engine	10.00	Small E85 Engine	5.00
Chassis	Vehicle Body	1247	Vehicle Body	1247	Vehicle Body	1247	Vehicle Body	1247
Subtotal		1676.76		1656.56		1790.96		1740.76
Misc.		63.43		67.80		56.93		100.52
Mechanical Accessories		60.00		60.00		60.00		60.00
Margin of Error		80.00		80.00		80.00		80.00
Total		1880.19		1864.36		1987.96		1981.28

The weight distribution is calculated by calculating the weight contribution of the components on each axle by estimating the components distances from the axles. This gives a good estimate of the weight distribution of the vehicles. The traction available on each axle depends on the percentage of the weight on that axles. This will help simulate more accurate performance results.

Table 3 : Weight Distribution

	SERIES – TV - C	**SERIES – TV - C**	**SERIES – TV - C**	**SERIES – TV - C**
Front	44.2%	44.2%	47.0%	45.5%
Rear	55.8%	55.8%	53.0%	54.5%

DESIGN TARGETS

The performance, energy consumption and criteria emissions results of modeled vehicles are tested against the design targets. This will validate these vehicles as possible vehicle architectures to meet this vehicle design specification. **Table 4** shows the design specification the vehicles under study should satisfy.

Table 4 : Design Specification

	Specification	Target	Units
Performance	Acceleration, IVM-60 mph	5.9	sec
	Acceleration, 50-70 mph (Passing)	7.3	sec
	Highway Gradebility, @ 20 min	6% @ 60 mph	% Grade @ mph
	Total Vehicle Range	240	km
Energy Consumption	UF-Weighted Total Energy Consumption	700	Wh / km
	UF-Weighted WTW Petroleum Energy Use	420	(Wh PE) / km
Emissions	UF-Weighted WTW Greenhouse Gas Emissions	225	(g GHG)/ km

VEHICLE SYSTEM MODELING

The modeling is done in Autonomie and MATLAB / Simulink programming environments. Autonomie is a Graphical User Interface (GUI) over MATLAB / Simulink that helps stitch all the powertrain components, controllers and the driver model together. It also does the post processing calculations of the model results.

The modeling techniques discussed in **Power loss modeling** is used to implement four vehicle architectures to simulate acceleration, dynamic energy consumption, and energy efficiency. Autonomie Version 13, Service-Pack 3 is used to model vehicle petroleum and electric energy-loss as a function of vehicle speed across a linear trajectory. Physical and logic-level features of each powertrain component in the vehicle model are emulated using a generic Matlab Simulink model and constrained to manufacturer specifications using a '.m' initialization file. Components are configured to represent the UW architecture by connecting the component module outputs via XML. The end result is a large system level vehicle model compiled in Simulink where energy loss is controlled using a provided hybrid vehicle supervisory controller model.

Auxiliary models include driver and environment models to represent driver torque requests as a function of simulated linear speed trajectory and environment variables including air density and acceleration due to gravity. Pre and post-processing files are used to configure the vehicle model and extract pertinent data.

Vehicle Powertrain Models

An example of the powertrain component configuration of the vehicle model is shown in **Figure 8**. All energy flow and control signals generated by the powertrain component models are compiled into a main powertrain information bus, which is broadcasted to the vehicle supervisory controller and driver model. Similarly, the supervisor also broadcasts its control signals through the main information bus.

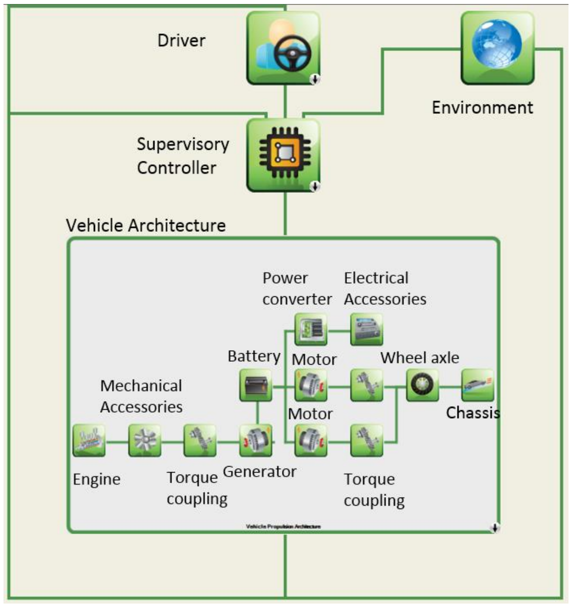


Figure 8 : Vehicle Model Layout in Autonomie (Series-TV Configuration)

Energy sources for the given vehicle model are petroleum energy represented by the engine model and electric energy represented by the ESS model. Energy loss is calculated according to efficiency look-up tables of each powertrain component with the majority of energy expelled to overcome inertial, aerodynamic drag, and rolling resistance forces of the vehicle represented primarily by the chassis and wheel models.

Powertrain Component Models

Each generic component model of Autonomie is parameterized to represent accurately the powertrain components used in the four vehicle architecture.

Engine Model

The major parameterizations needed for the generic engine model are the power output curve, volumetric efficiency map, and the fuel map. The engine model heavily relies on dynamometer data of a real engine on a test bench. **Figure 9** shows the power curve of the VFR 800 engine used to power the generator motor for the Series-TV-A/B and the Series-AWD. Because of a lack of engine dynamometer data for the VFR 800, an approximation of the volumetric efficiency and the fuel map is back calculated from dynamometer results of other E85 and motorcycle engines.

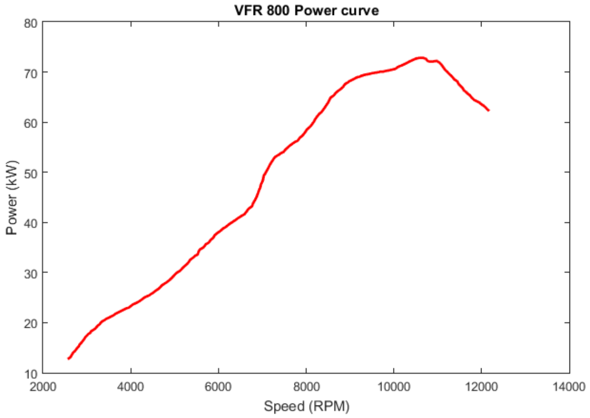


Figure 9 : Honda VFR 800 Power Curve

Unfortunately, the GM 2.4L LEA engine data is proprietary and cannot be shared.

Generator and Rectifier Model

The generator motor and controller (used as a rectifier) are modeled as one unit, because the pair can be represented as a simple power-loss model. While it is a low-fidelity model, it is sufficient if the efficiency losses of the controller are accounted for. **Figure 10** and **Figure 11** demonstrates the peak and continuous output torque curves of the SMG 180 generator motor and the Enstoj Emrax 228 respectively.

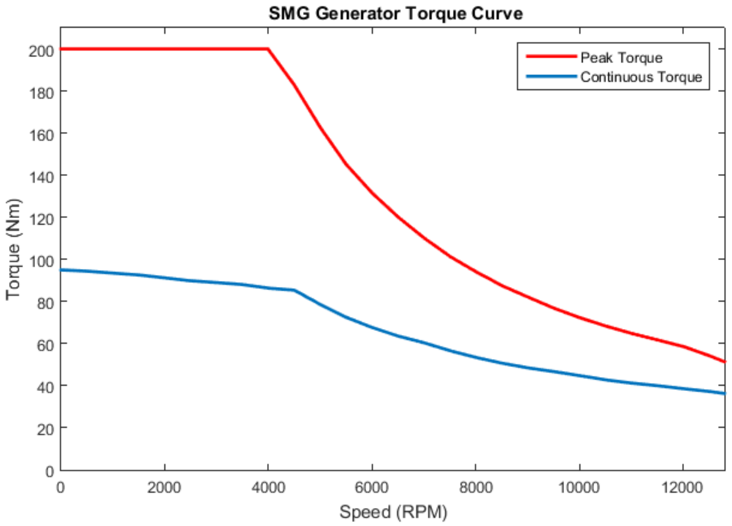


Figure 10: Bosch SMG 180 Torque curves [2]

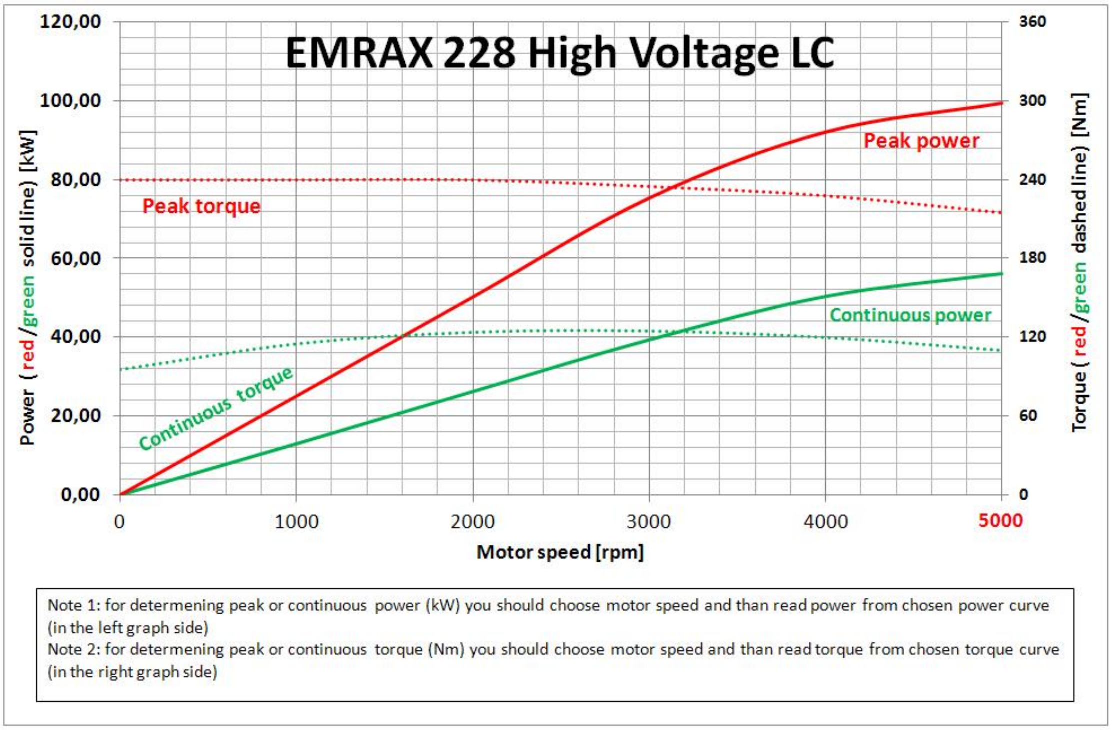


Figure 11 : Enstroj Emrax 228 Torque and Power curves [3]

Efficiency data for the SMG 180 are interpolated from the component operating points provided by Bosch [2]. The Efficiency data for the Enstroj Emrax 228 is shown in **Figure 12**.

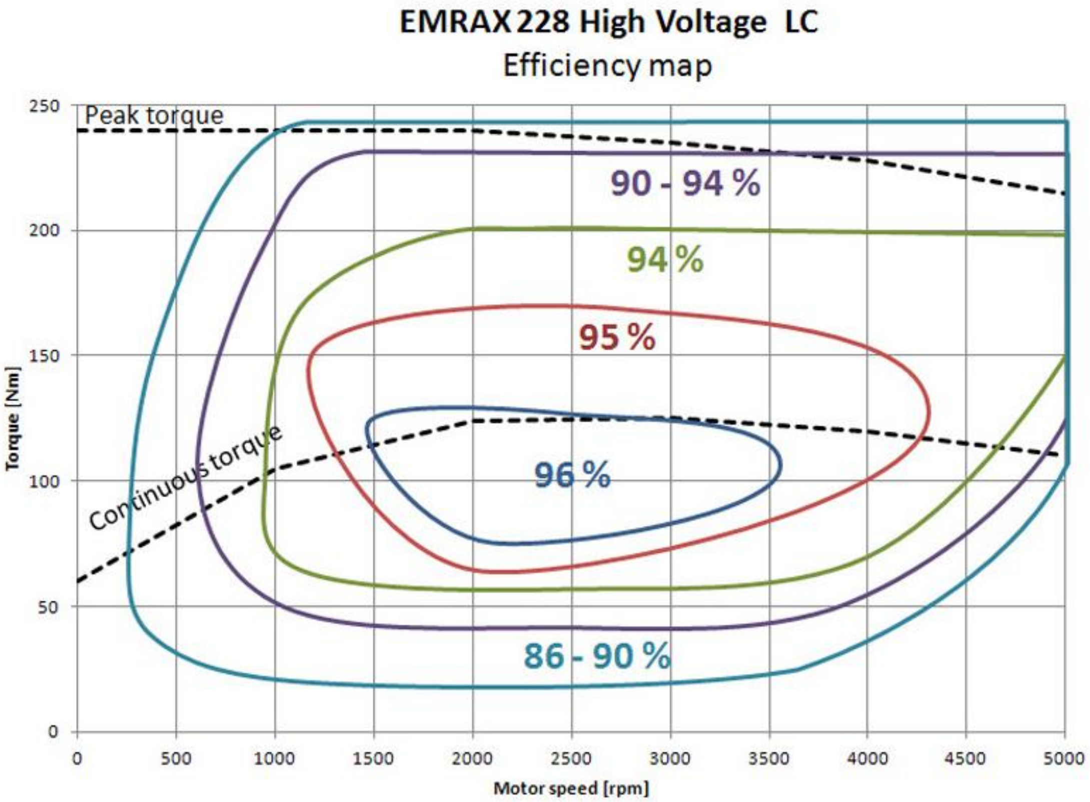


Figure 12 : Enstroj Emrax 228 Efficiency Data

Energy Storage System (ESS) Model

The ESS model is built by parameterizing cell terminal characteristics according to the electrolyte chemistry used and manufacturer specifications. The ESS system terminal characteristics are modeled by arranging the modeled cells in the same fashion as the ESS manufacturers [4] [5]. Some cell characteristics including internal resistance, open circuit voltage, and charge and discharge limits proportionally depend on the cell state-of-charge (SOC). Table 5 shows the some ESS data given by the manufacturers.

Table 5 : ESS Data [4] [5]

Characteristics	A 123 Pack	Enerdel Pack
Cell Chemistry	Lithium-Ion	Lithium-Ion
Cell Min Capacity (Amp-Hr)	19.6	14.3
Cell Max Voltage (V)	3.6	3.6
Cell Nominal Voltage (V)	3.24	3.24
Cell Min Voltage	2.5	2.5
Cells in parallel	3	2
Pack Series cells per module	15	12
Modules per pack	7	8
Pack V_{max} (V)	378	394
Pack V_{nom} (V)	340	350
Pack V_{min} (V)	263	240
Min Pack Capacity (A-Hr)	58.8	28.6
Min Pack Energy (kW-Hr)	18.9	11.2

Traction Motor and Inverter Model

The traction motors and controllers (used as an inverter) are modeled similar to the generator motor and controller, each traction motor and accompanying controller are modeled as one unit. **Figure 13**, **Figure 14**, and **Figure 15** shows the Torque curves of the Enstroj Emrax 268, Remy HVH250, and GKN AF-130 which are the traction motors used among the vehicle architectures.

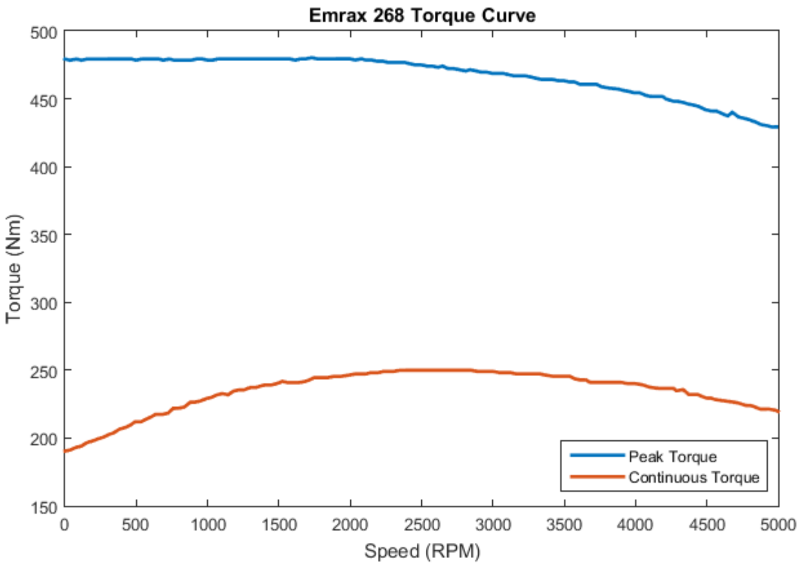


Figure 13 : Enstroj Emrax 268 Torque Curve

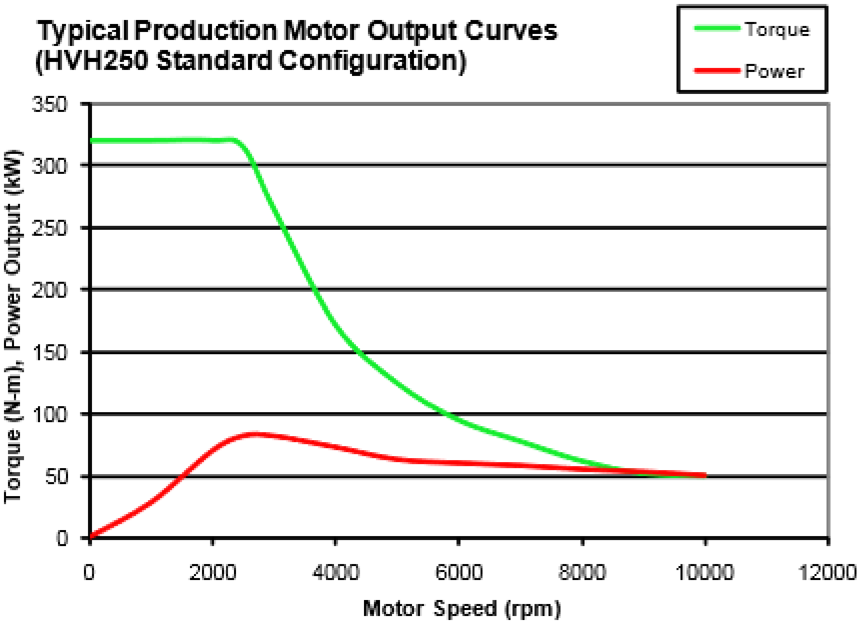


Figure 14 : Remy HVH250 Torque Curve

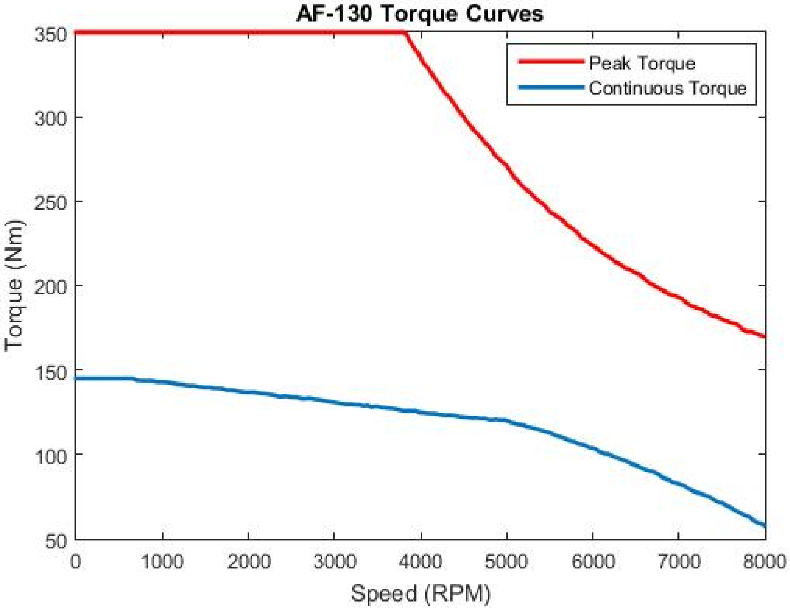


Figure 15 : GKN AF-130 Torque Curve

The efficiency data used to model the traction motors are shown in **Figure 16**, **Figure 17**, and **Figure 18**.

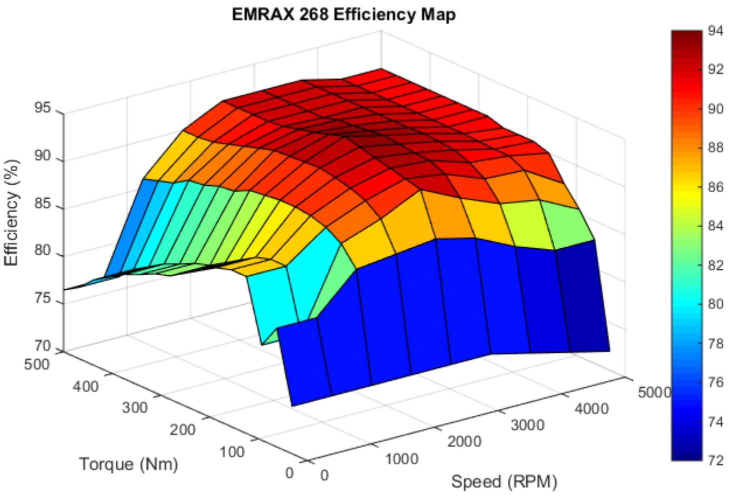


Figure 16 : Enstroj Emrax 268 Efficiency Data

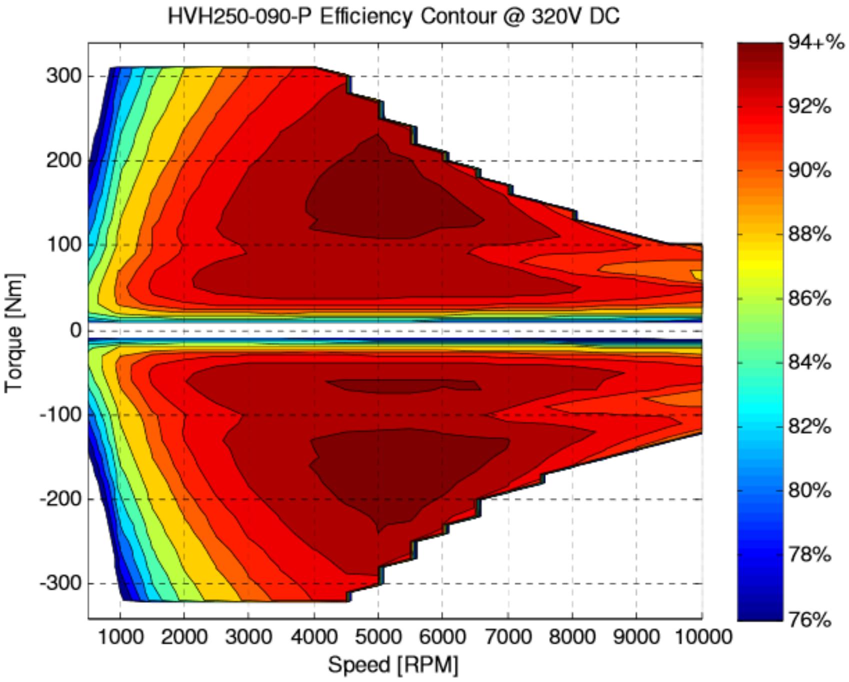


Figure 17 : Remy HVH250 Efficiency Data

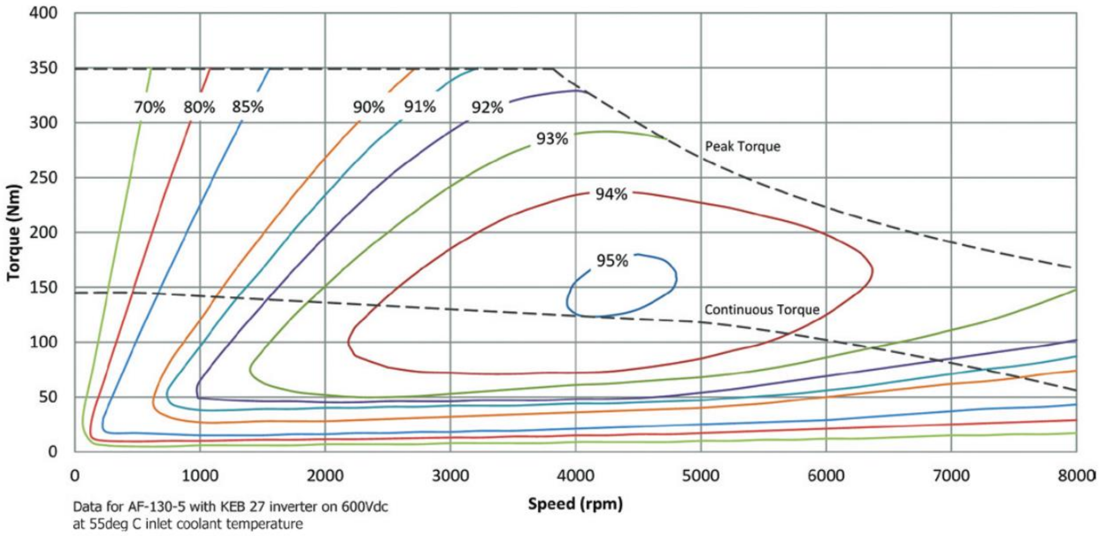


Figure 18 : GKN AF-130 Efficiency Data

Chassis and Wheel Models

The chassis and the wheel models incorporate the road load losses. The chassis model includes grade losses **Equation 2** as well as the aerodynamic losses **Equation 4**. The wheel model includes rolling friction losses **Equation 3**.

Mechanical and Electrical Accessories Models

These models are set to have constant energy losses to simulate the mechanical losses and electrical accessories such as hydraulic brakes and fuel pumps. As a result, these components are emulated as simple power-loss models using energy multipliers.

Supervisory Controller Model

The supervisory controller model generates all control signals needed to operate all powertrain components in the vehicle model. The primary function of the supervisory controller is to send the appropriate torque requests to the motors and generator as a function of the driver model input. Torque requests are primarily based off of the ESS SOC and vehicle operating mode. Two separate sub-systems within the controller are used for propulsion control and brake control. The two command signals from these sub-systems are merged appropriately to achieve the command signals to the vehicle component models. In the propulsion controller subsystem, the vehicle-operating mode is selected. **Figure 19** shows the schematic layout of the supervisory controller.

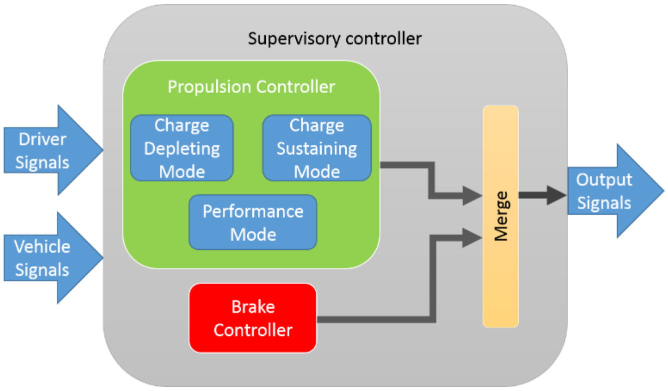


Figure 19: Schematic layout of the Supervisory Controller Model

Driver Model

The driver model used for this vehicle model is a Time - Based look ahead driver model. A look ahead model reads the drive trace a specified time ahead of its run time. This helps estimate the acceleration/deceleration required ahead of time, thus the vehicle better tracks of the drive trace. **Figure 20** shows the schematic layout of the Driver model. First the model takes in the vehicle current speed and the drive trace. It looks ahead in the drive trace and calculates the force need to accelerate/decelerate. The torque request is sent to the Torque demand estimator which adds the losses that will be incurred by due to the road load losses. Finally this torque demand will be sent out as an accelerator pedal request or a brake pedal request depending on the required acceleration/deceleration.

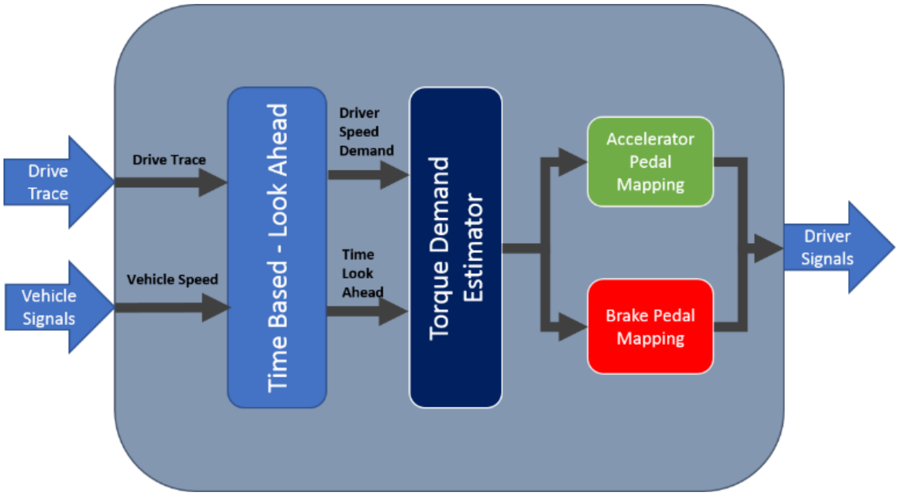


Figure 20 : Schematic layout of the Driver Model

DRIVE CYCLES

The goal is to estimate the approximate Energy consumption, emissions, and performance of these vehicle architectures. Performance testing includes 0-60mph acceleration, passing maneuver (50-70mph) and gradeablilty.

Energy Consumption and Emissions Drive cycle

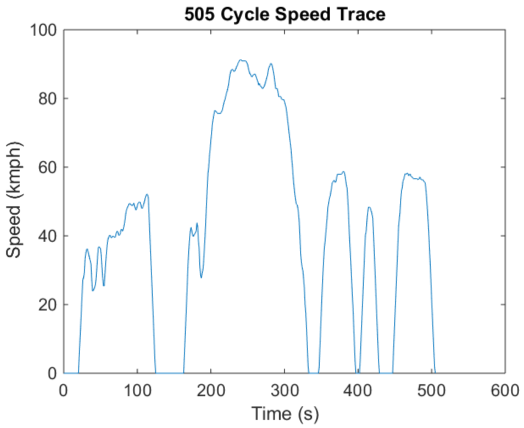


Figure 21 :505 Cycle

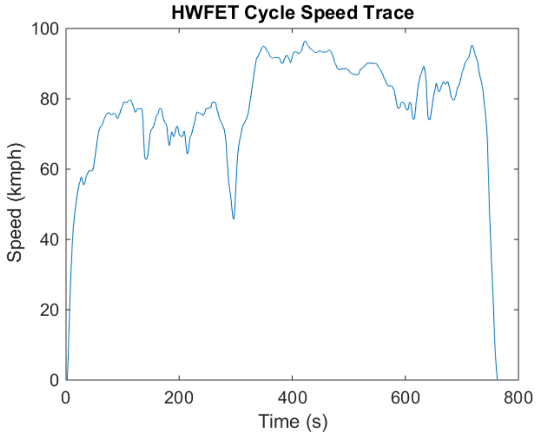


Figure 22 : HWFET Cycle

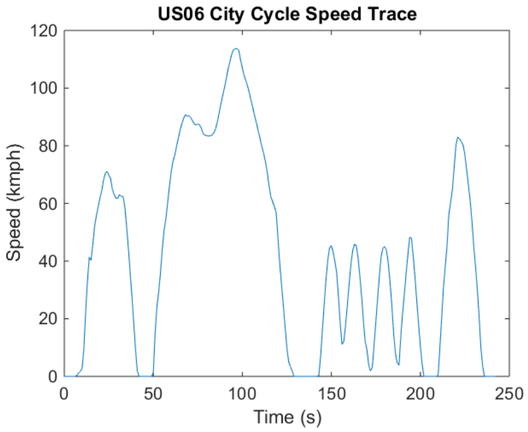


Figure 23 : US06 City Cycle

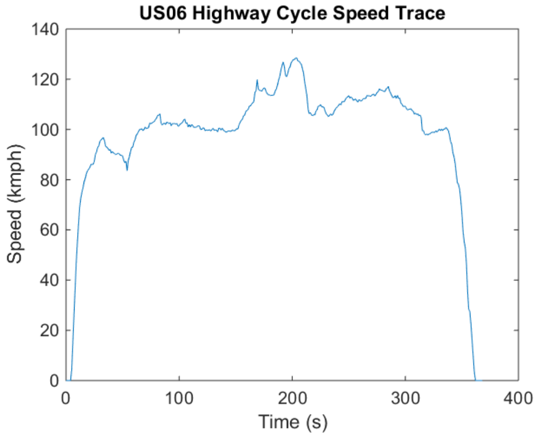


Figure 24 : US06 Highway

Four drive cycles that simulate different drive cycles that emulate daily driving routines of different kinds of drivers are weighted differently to estimate the energy consumption and emissions of the vehicle architectures. The four chosen are the 505 cycle (**Figure 21**), the HWFET cycle (**Figure 22**), US06 City cycle (**Figure 23**), and US06 Highway cycle (**Figure 24**). **Table 6** shows the weights and basic characteristics of the drive cycles.

Table 6 : Drive Cycle Characteristics

Drive Cycle	Characteristics	Avg. Speed (kmph)	Avg. Acceleration (m/s)	Weighting Factor for Drive Cycle (%)
505	Low speed	41	0.51	29%
HWFET	Mid speed	77.7	0.19	12%
US06 City	Low speed, aggressive	44.2	1.29	14%
US06 Highway	High speed, aggressive	98.5	0.34	45%

Performance Tests

Acceleration Test

Acceleration test includes 0-60mph and 50-70mph (Passing maneuver). The driver is made to give 100 % pedal request by requesting a very high speed request. Once the vehicle reaches the speed, the time vectors are measured to obtain the acceleration times needed.

Gradeability Test

This is a test that checks if the vehicle is able to climb a 6% grade at 60 mph for 20 minutes. Since this test on real vehicles is done by attaching a dyno trailer to the vehicle, it is important to add some weight to the vehicle to account for the weight of the dyno trailer used while testing the actual vehicle.

POWER, SPEED AND TORQUE REQUIREMENTS

Power, speed, and torque requirements for the four selected vehicles are analyzed mathematically to ensure the vehicles can meet trace. The force requirement of each drive cycle is calculated by differentiating the drive trace and multiplying the result with the calculated weights of the vehicle under study. The road load losses i.e. rolling friction and aerodynamic losses are added to the force requirement. This provides the force output requirements of the powertrain to meet trace. Multiplying the required force with the wheel diameter gives the required torque. Multiplying the wheel speed and required wheel torque, the required power to propel the vehicle is calculated. The four proposed vehicles have different power train components, and the ability for each to provide power in all the operating modes are discussed individually.

SERIES-TV-A/B

Since the SERIES -TV-A and the SERIES -TV-B have similar weights and powertrain components apart from the generator. The power torque speed requirements analysis can be done together. The minimum motor power available for the SERIES -TV-(A/B) architectures is calculated by multiplying the motor speed with the corresponding continuous motor torque available. The motor speeds are calculated by multiplying the angular velocity of the wheels with the fixed gear ratio. Since these vehicles have two identical motors operating at the same speed, the power available at one motor can be calculated and doubled to obtain the total power available across both motors. The power required is divided by the voltage of the ESS at 15 % SOC to show the worst case current requirement. Since the two SERIES -TV vehicles have the same tractions motors, resulting values are the same.

Power and Torque Requirements

Figure 25 shows the power requirements and available power by the SERIES -TV-(A/B) vehicles. This shows that the vehicle is capable of meeting the required accelerations required.

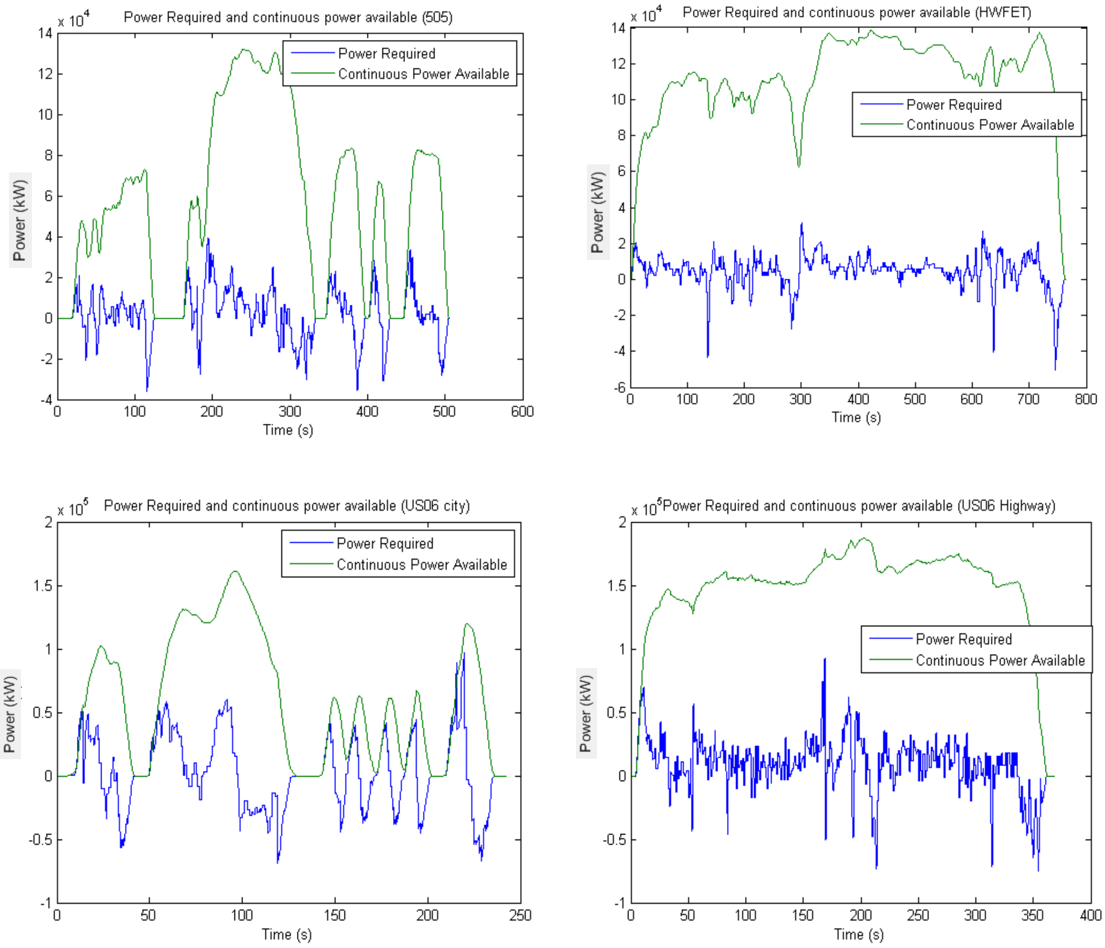
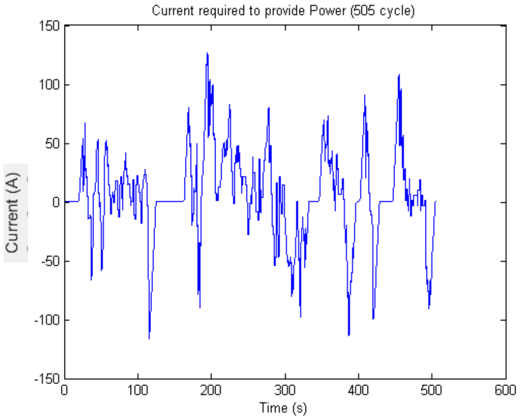
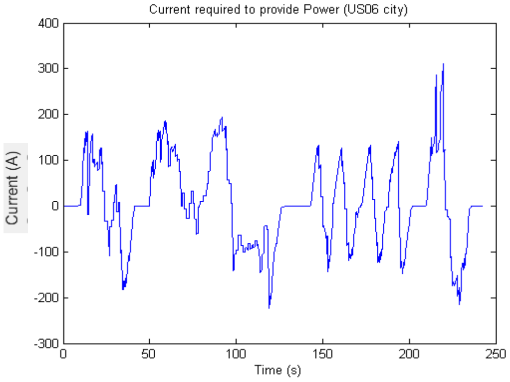


Figure 25 : Power Requirements by SERIES-TV-A/B

Current Requirements





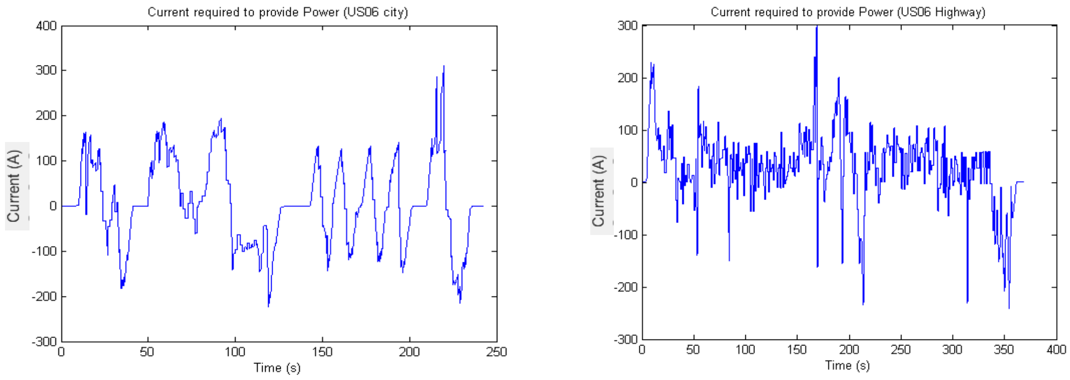


Figure 26 : Current Requirements by SERIES-TV-A/B

Figure 26 in the shows the current requirements for the four cycles. Table 7 shows the maximum current requirement and mean positive current draw by SERIES-TV-A/B vehicles. The Bosch SMG 180 coupled with the Honda VFR 800 can produce a maximum continuous current of 109.5 A and the EMRAX 226 coupled with the Honda VFR 800 can produce a maximum continuous current of 157.48 A.

In charge depleting mode, the 18.9 kWh A123 ESS has a peak current output of 600 A for approximately two seconds and a continuous current output of 300 A, allowing the vehicles to meet the current draw requirements. This establishes that an all-electric charge depleting mode is possible.

In charge sustaining mode the SERIES -TV-A and the SERIES -TV-B can produce current that is sufficient to maintain the ESS SOC as the average current draw is less than 43 A in all cycles. The ESS will have to provide current at high current demands, but that current can be put back in the pack by the generators during the drive cycles.

Table 7 : Maximum and Mean Positive current draw for the SERIES RWD TV A/B Vehicles

CYCLE	MAXIMUM Current Draw (A)	MEAN Positive Current Draw (A)
505	127.1	15.36
HWFET	101.31	20.26
US06 City	311.29	37.37
US06 Highway	299.26	42.54

Speed Requirements

Both SERIES-TV-A/B vehicles have the EMRAX motors coupled to a gear box with a ratio 4.2. Taking the maximum operating speed of the motor as 4500 rpm and considering the maximum motor speed is 5000 rpm, the top speed of the vehicle is calculated to be 137 km/hr, which is 8 km/hr above the maximum speed demanded by the four cycles.

SERIES-TV-C

The calculations for the SERIES -TV-C is similar to the SERIES -TV-A/B, the only differences are the mass of the vehicle, the current output of the generator set, and the ENERDEL ESS voltage.

Power and Torque Requirements

Figure 27 shows the power requirements and available power by the SERIES -TV-(A/B) vehicles. This shows that the vehicle is capable of meeting the required accelerations required.

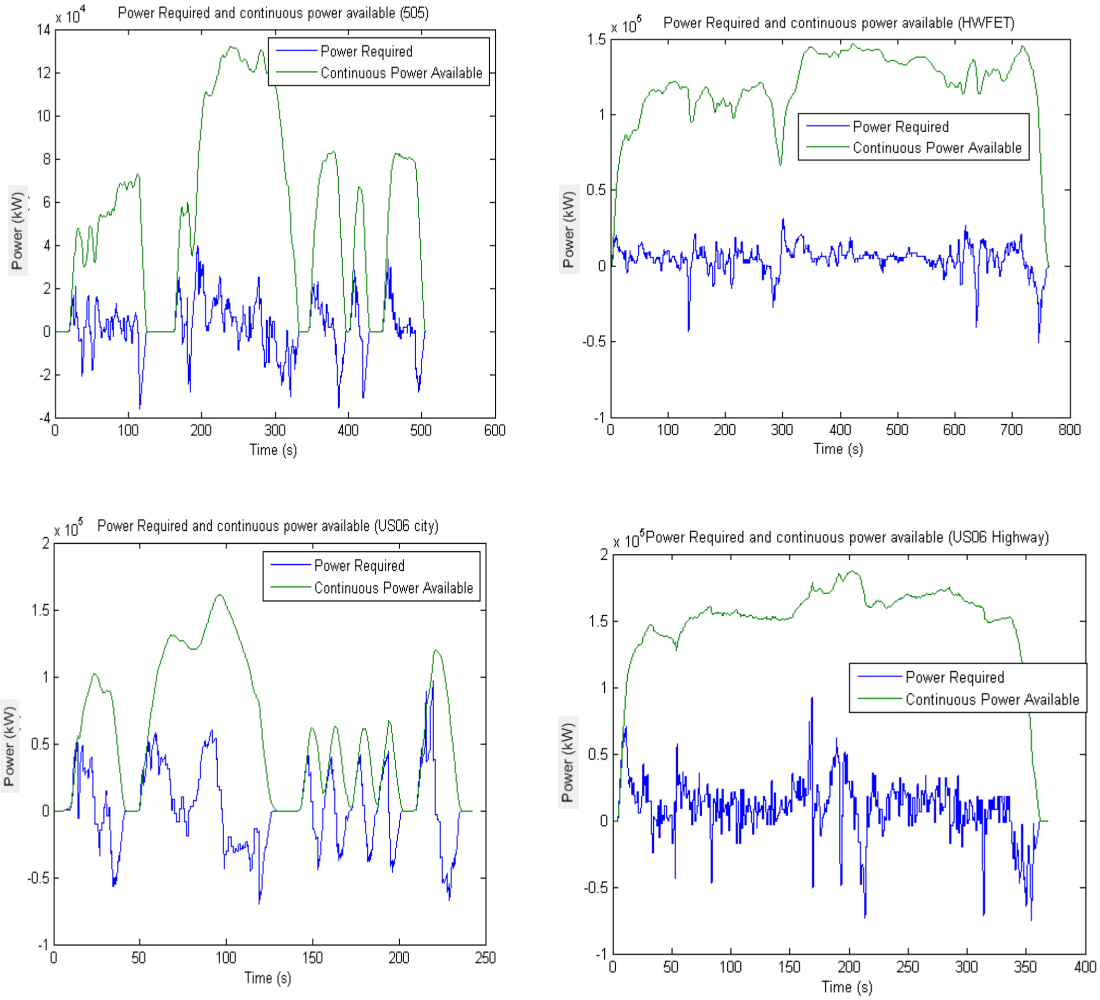
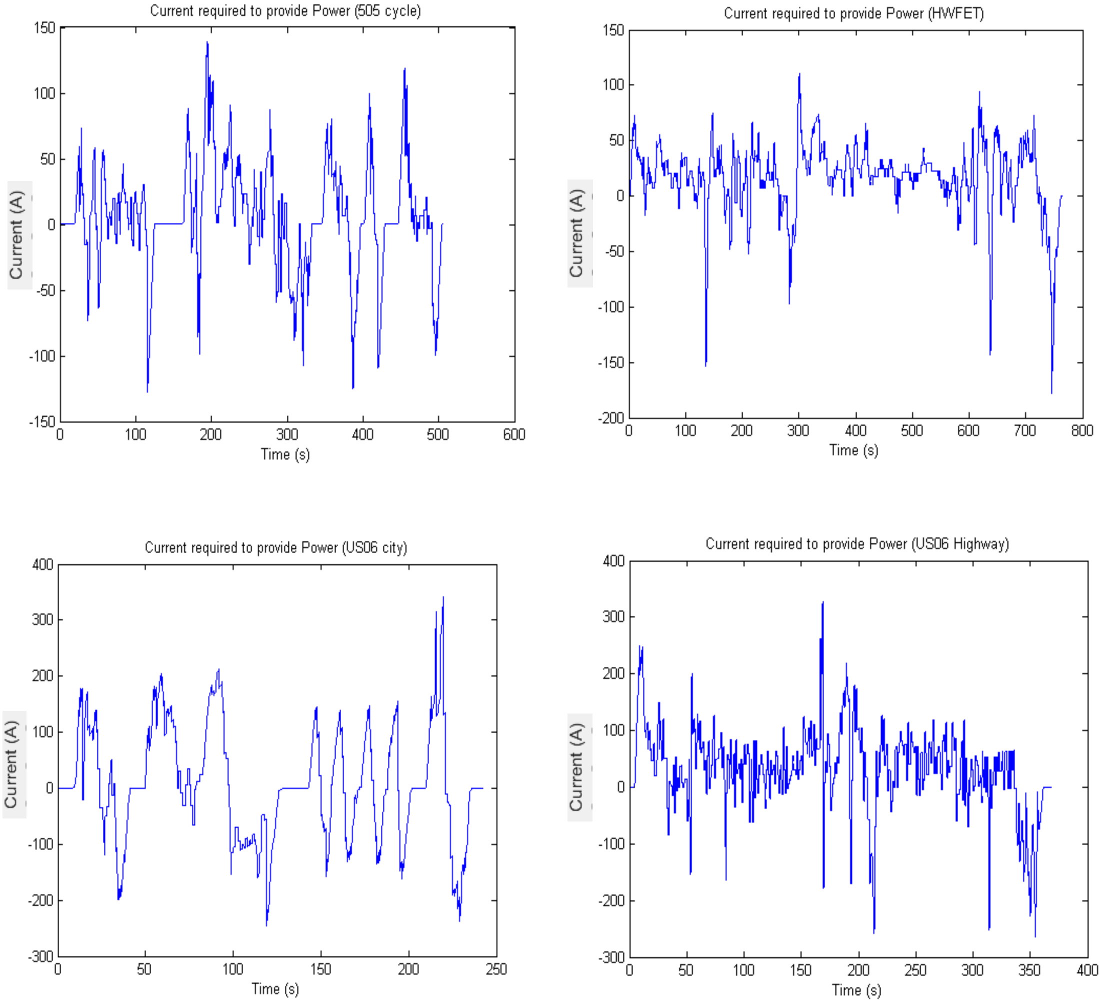


Figure 27 : Power Requirements by SERIES-TV-C

Current Requirements


Current required to provide Power (505 cycle)

Current required to provide Power (HWFET)

Current required to provide Power (US06 city)

Current required to provide Power (US06 Highway)

Figure 28 : Current Requirements by SERIES-TV-C

Figure 28 shows the current requirements for the four cycles. Table 8 shows the maximum current requirement and mean positive current draw by SERIES-TV-C vehicle. The Remy HVH 250 coupled with the GM LEA 2.4 L engine can produce a maximum continuous current of 173.96 A.

In charge depleting mode, the 11.2 kWh ENERDEL ESS has a peak current output of 320 A for approximately two seconds and a continuous current output of 180 A. As a result, the Series-TV vehicle can only meet the current draw requirements if the generator assists at low SOCs. This means that an all-electric charge depleting mode is not possible.

In charge sustaining mode, the SERIES -TV can produce current that is sufficient to maintain the ESS SOC as the average current draw is less than 47 A in all cycles. The ESS will have to provide some current at high current demands, but that current can be put back in the ESS by the generator during the drive cycles to maintain the SOC of the ESS.

Table 8 : Maximum and Mean Positive current draw for the SERIES RWD TV C

CYCLE	MAXIMUM Current Draw (A)	MEAN Positive Current Draw (A)
505	139.31	16.83
HWFET	111.03	22.18
US06 City	341.17	40.95
US06 Highway	327.92	46.58

Speed Requirements

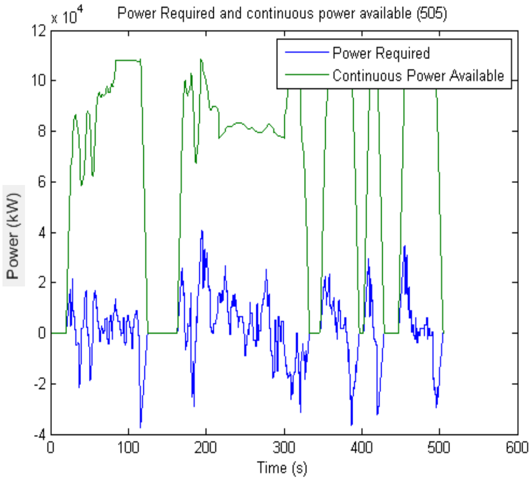
The SERIES -TV vehicle has the same powertrain components putting power to the ground as the SERIES TV. Hence, the speed calculations are identical to the SERIES TV vehicles. This puts its top seed as 136 km/hr when the speed requirement is 129 km/hr.

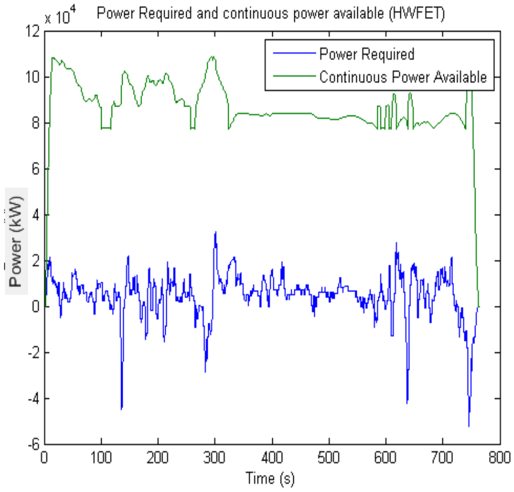
SERIES-AWD

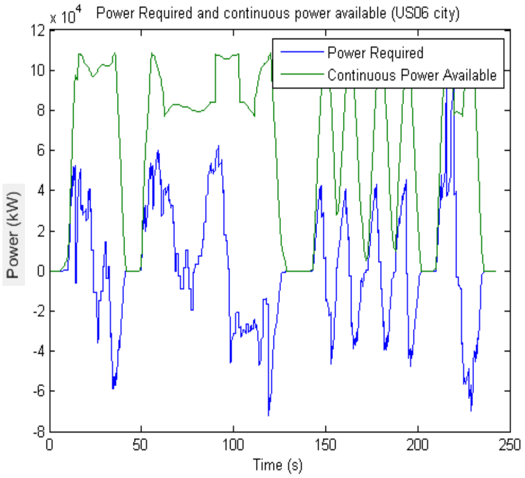
The power required is calculated similar to the EREV-TV-A/B, but the 2- speed transmission in this architecture determines the power available. The script used to calculate the available motor power takes in to account the motor speed and determines the gear that the vehicle is in and sets the motor power accordingly.

Power and Torque Requirements

Figure 29 shows the power requirements and available power by the SERIES -TV-(A/B) vehicles. This shows that the vehicle is capable of meeting the required accelerations required.







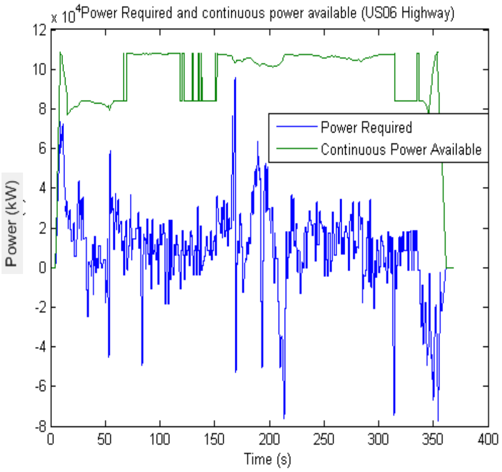


Figure 29 : Power Requirements by SERIES-AWD

Current Requirements

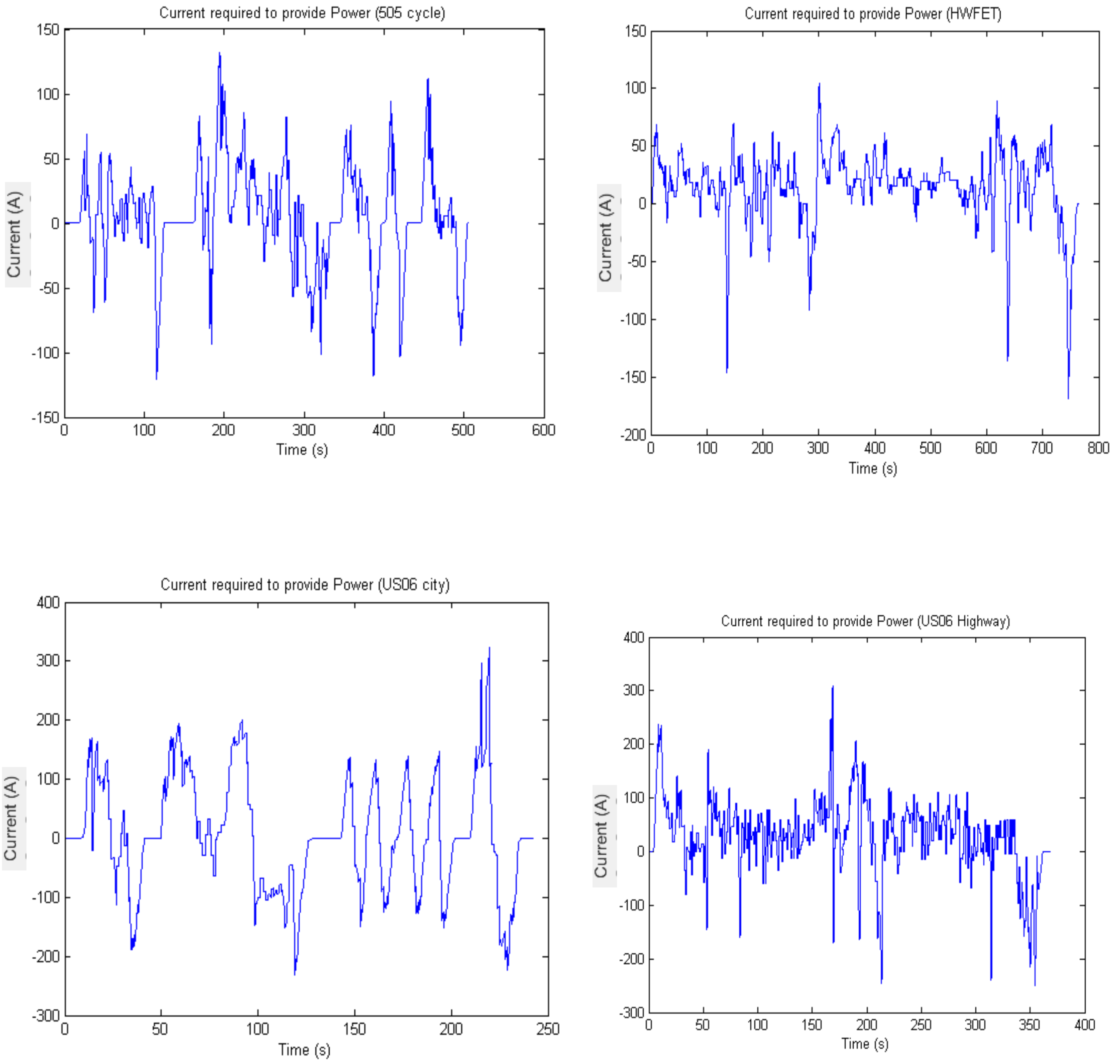


Figure 30 : Current Requirements by SERIES-AWD

Figure 30 shows the current requirements for the four cycles. **Table 9** shows the maximum current requirement and mean positive current draw by SERIES-AWD vehicle. The Bosch SMG 180 coupled with the Honda VFR 800 can produce a max continuous current of 109.5 A.

In charge depleting mode, the 18.9 kWh A123 ESS has a peak current output of 600 A for approximately two seconds and a continuous current output of 300 A. As a result, the SERIES -AWD vehicle is able to meet the current draw requirements. This establishes that an all-electric charge depleting mode is possible.

In charge sustaining mode, the SERIES -AWD with a Bosch SMG 180 can produce current which is sufficient to maintain the ESS SOC as the average current draw is less than 44 A in all cycles. The ESS will have to provide current at high current demands, but that current can be put back in the pack by the generators during the drive cycles.

Table 9 : Maximum and Mean Positive current draw for the SERIES AWD Vehicle

CYCLE	MAXIMUM Current Draw (A)	MEAN Positive Current Draw (A)
505	131.64	15.81
HWFET	104.87	20.59
US06 City	322.27	38.62
US06 Highway	308.67	43.32

Speed Requirements

The EREV-AWD vehicle has two motors, the AF-130 being the slower one. Taking the AF-130 max operating speed of 7500 rpm coupled with the smaller gear ratio of the GKN 2-speed gearbox (5.95) as the speed limiting factors, the top speed of the vehicle is calculated to be 160 km/hr. This is well above the 129 km/hr speed requirement.

SYSTEM LEVEL POWERTRAIN CONTROL STRATEGIES

Each architecture has three main powertrain modes: charge depleting mode (CD), charge sustaining mode (CS), and performance mode.

Generator Control – All Vehicles

In all three modes, the four vehicles will have the same control strategy for the ICE Engine/Generator Motor (genset), the VFR 800 / SMG 180 Gen 1 for EREV-TV-A and EREV-AWD, VFR 800 / EMRAX 228 for the EREV-TV-B, and LEA 2.4L / HVH250-90P for the Series-TV. In CD mode, the vehicle will attempt to run without any power from the genset. If the ESS is unable to provide enough power to meet driver demands, the genset will start and provide the difference. The vehicles will run in CD mode until the vehicle SOC is around 15% then transition into CS mode, where the engine is primarily on. In simulation, the only exception is when the vehicle is at a stop. The genset is allowed to temporarily shut down. The control for the genset is a standard load-following algorithm, prioritizing efficiency and keeping the SOC of the ESS in a narrow range of a 15% target. If the SOC drops too low, the algorithm will transition to prioritizing charging the ESS over running the engine efficiently. For the control strategy implemented on the actual vehicle, the effects of shutting down the genset at a stop and other times will be tested for both energy consumption and emissions. Also, a more advanced algorithm will be used to load the engine, such as low frequency load following, which draws on the strengths of the particular engine.

Traction Motor Control: Torque Vector Architecture (ALL SERIES –TV Vehicles)

In simulation, equal torque is commanded to each traction motor in all modes for all three vehicles. The actual vehicle itself, however, will have to have a more sophisticated torque-blend of the two motors in order to achieve the functionality of a differential. Further gains in handling can be made by implementing true torque-vectoring at a later point.

In performance mode, the engine is run at all times and the SOC is kept as high as possible to allow maximum current discharge to the drive motors at all times. Priority is maximum power output over efficiency.

Traction Motor Control: SERIES -AWD

For CD and CS mode, only the motor with the lowest energy loss is used at any given time. Independent of whether a motor is currently in use, gear selection is based off maximum rpm of the motor in first gear. If a motor can be in first gear and not be above its maximum rpm threshold, it will either remain in first gear or switch to first gear. Otherwise, it will remain in second gear or switch to second gear.

In performance mode, the engine is run at all times and the SOC is kept as high as possible to allow maximum current discharge to the drive motors at all times. Priority is maximum power output over efficiency.

ENERGY CONSUMPTION AND EMISSIONS CALCULATIONS

Post-processing of simulation results to find energy consumption and greenhouse gas emissions involves using the equations and emissions factors provided in the Non Year Specific rules. Energy consumption is typically given in units of kilowatts per kilometer. However, since simulation results from Autonomie are given in terms of grams per kilometer, **Equation 5** must be used in conjunction with E85 fuel specific energy given in

Table 10.

Equation 5

$$\boldsymbol{Energy\ Consumption_{Fuel}, EC_{Fuel}\left[\frac{kWh}{km}\right] = \left(\frac{Fuel\ consumed\ [g]}{1000}\right) * Fuel - specific\ energy\left[\frac{kwh}{kg}\right]}$$

Charge Depleting Mode

Energy consumption in charge depleting mode is the sum of electric and fuel energy consumed. Since the ESS is able to fulfil driver demand in all drive cycles no fuel is consumed during charge depleting mode.

Equation 6

$$\boldsymbol{Energy\ Consumption_{CD}, EC_{CD}\left[\frac{kWh}{km}\right] = EC_{electric,CD} + EC_{fuel,CD}\left[\frac{kWh}{km}\right]}$$

Charge-Sustaining Mode

Energy consumption in charge sustaining mode is calculated using an equivalent fuel energy consumption value which has been SOC corrected. The value must be SOC corrected due to energy that is supplied to the ESS but not used. **Equation 9** shows that the SOC corrected fuel consumption depends on the electric energy consumption, which is negative for the four cycle blended results, leading to a lower value for fuel consumption which agrees with the fact that some of the fuel consumed ended up being stored in the ESS.

Equation 7

$$\boldsymbol{Energy\ Consumption_{CS}, EC_{CS}\left[\frac{kWh}{km}\right] = EC_{equivalent\ fuel\ ,CS}\left[\frac{kWh}{km}\right]}$$

Where

Equation 8

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

Where

Equation 9

$$\boldsymbol{FC_{SOC-corrected}\left[\frac{kg}{km}\right] = \frac{Mass_{fuel}[kg] + \frac{EC_{electric,CS}[kWh]}{0.25} / FSE_{E85}\left[\frac{kWh}{kg}\right]}{Cycle\ distance\ [km]}}$$

Where FSE_{Gas} is the Fuel Specific Energy of Gasoline found in Table 10.

Table 10: Energy Source Characteristics

Energy Source Characteristics	E85 Specification	Gasoline Specification	Electricity Specification
Fuel-specific energy by mass (kWh/kg)	7.96	11.73	n/a
Fuel density (kg/L)	0.7871	0.7583	n/a
Fuel energy density by	6.265	8.895	n/a

volume (kWh/L)			
Fuel energy density by volume (kWh/gal)	23.7	33.7	n/a
PEU_{WTP} (kWh PE/kWh fuel consumed)	0.063	n/a	0.033
PEU_{PTW} (kWh PE/kWh fuel consumed)	0.21	n/a	0
PEU_{WTW} (kWh PE/kWh fuel consumed)	0.274	n/a	0.033
GHG_{WTP} (g GHG/kWh of fuel consumed)	-15.39	n/a	488.6
$(CO_2)_{PTW}$ (g/kWh)	260	n/a	0
GHG_{WTW} (g/kWh)	244	n/a	489

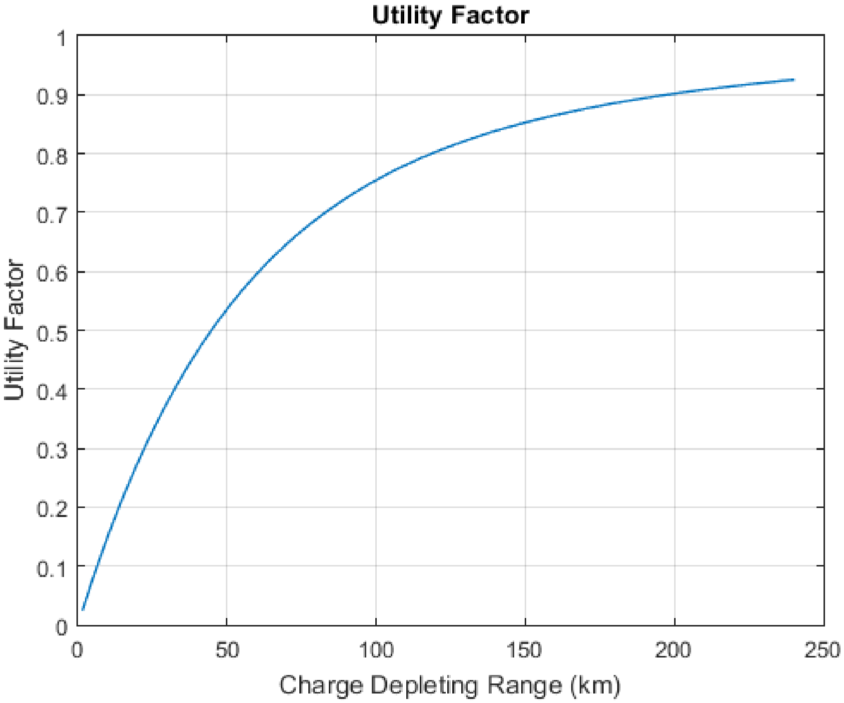
Utility Factor

For Plugin Hybrid Electric Vehicle (PHEV) vehicles, fuel and energy consumption rates vary depending on distance driven between charging. Some drivers may spend drive further than others, and thus spend more time in charge sustaining mode leading the higher consumption versus other drivers. The utility factor is used to weight energy and fuel consumption for PHEVs based on data from the National Household Travel Survey. The definition of the UF comes from SAE J2841 and the SAE J1711 test method. The UF represents the percentage of vehicles that will use the charge depleting range in a day, with the remaining 1-UF being used to weight the charge sustaining energy consumption of the rest of drivers on that day. One crucial assumption of the regarding the UF is the vehicle operation starts at full charge every day. **Equation 10** creates a UF curve based on the vehicles charge depleting range.

Equation 10

$$Utility\ Factor, UF = 1 - \ exp^{-\left[\sum_{n=0}^{6} Cn*\left(\frac{x}{Dnorm}\right)^{n}\right]}$$

Where Dnorm = 399.9 and C1 through C6 = 10.52, –7.282, –26.37, 79.08, –77.36, and 26.07.



All modes combined Energy Consumption

Utility Factor-Weighted Energy Consumption

The UF weighted total energy consumption scales the energy consumption in both charge sustaining and charge depleting modes.

These two results are added to determine the total UF adjusted energy consumption for the vehicle.

Equation 11

$$\boldsymbol{Energy\ Consumption_{UF-weighted}, EC_{UF}\left[\frac{kWh}{km}\right] = EC_{CD}\left[\frac{kWh}{km}\right] * UF + EC_{CS}\left[\frac{kWh}{km}\right] * (1 - UF)}$$

Gasoline equivalent Fuel Consumption

The gasoline equivalent fuel consumption takes the UF weighted energy consumption and uses the Fuel Specific Energy to find the fuel consumption in terms of kilograms per kilometer.

Equation 12

$$Fuel\ Consumption_{Gasoline\ Equivalent}, FC_{GE}\left[\frac{kg}{100\ km}\right] = \left(\boldsymbol{EC_{UF}\left[\frac{kWh}{km}\right]} \middle/ \boldsymbol{FSE_{Gas}\left[\frac{kWh}{kg}\right]} \right) * \mathbf{100}$$

Where FSE_{Gas} is the Fuel Specific Energy of Gasoline found in

Table 10.

Greenhouse Gas Emissions

To estimate the greenhouse gas emissions for the vehicle the energy consumption of fuel and electricity are calculated using **Equation 14** and **Equation 15.** Equation 13 is the combination of fuel energy consumption in charge depleting mode and well as the equivalent fuel consumption in charge sustaining mode, which has been SOC adjusted. These UF weighted energy consumption values are then multiplied by GHG emission factors from **Table 10**.

Equation 13

$$\begin{aligned}\boldsymbol{Greenhouse\ Gases_{Well-Wheel}, GHG_{WTW}\left[\frac{g}{km}\right]} \\ \boldsymbol{= EC_{Fuel-UF\ Weighted}\left[\frac{kWh}{km}\right] * GHG_{WTW,Fuel}\left[\frac{g}{kWh}\right]} \\ \boldsymbol{+\ EC_{Electricity-UF\ Weighted}\left[\frac{kWh}{km}\right]} \\ \boldsymbol{* GHG_{WTW,Electricity}\left[\frac{g}{kWh}\right]}\end{aligned}$$

Where

Equation 14

$$\begin{aligned}\boldsymbol{EC_{Fuel-UF\ Weighted}\left[\frac{kWh}{km}\right]} \\ \boldsymbol{= EC_{fuel,CD}\left[\frac{kWh}{km}\right] * UF + EC_{equivalent\ fuel\ ,CS} * (1 - UF)}\end{aligned}$$

And

Equation 15

$$EC_{Electricity-UF\,Weighted}\left[\frac{kWh}{km}\right] = EC_{electric,CD}\left[\frac{kWh}{km}\right] * UF$$

Petroleum Energy Usage

Similar to the greenhouse gas emissions, the petroleum energy usage is calculated by using given factors from the Non Year Specific rules multiplied by the UF weighted fuel and electrical energy consumption.

Equation 16

$$\begin{aligned} &Petroleum\ Energy\ Usage_{Well-Wheel}, PEU_{WTW}\left[\frac{g}{km}\right] \\ &= EC_{Fuel-UF\,Weighted}\left[\frac{kWh}{km}\right] * PEU_{WTW,Fuel}\left[\frac{g}{kWh}\right] \\ &+ EC_{Electricity-UF\,Weighted}\left[\frac{kWh}{km}\right] * PEU_{WTW,Electricity}\left[\frac{g}{kWh}\right] \end{aligned}$$

RESULTS

The vehicle models are run on the **Energy Consumption and Emissions Drive cycle**. The results are then combined with Argonne National Lab's Greenhouse Gas, Regulated Emissions and Energy Use in Transportation (GREET) model. The GREET model examines the energy use of a vehicle throughout an entire fuel-cycle, from well-to-wheel. Upstream factors in the fuel production process are projected fuel paths for 2020. To assist in calculations, a GREET calculation sheet is implemented in Excel to calculate emissions and energy consumption equations at once. The Performance results are calculated from the speed vs. time vector generated when running the performance drive cycle discussed in **Performance Tests** section.

As shown in Table 11 : Energy Consumption and Emission Results and Table 12 : Performance Results all the vehicles meet the design targets (Table 4 : Design Specification).

Table 11 : Energy Consumption and Emission Results

	4-Cycle Blended Results	SERIES-TV -A	SERIES-TV -B	SERIES-TV-C	SERIES-AWD
Charge Depleting	Utility Factor	0.69	0.69	0.53	0.69
	CD-Range (km)	79.3	79.3	48.75	80.2
	Rate of Electrical Consumption (Wh/km)	241	241	242	244
	Rate of Fuel Consumption (Wh/km)	0	0	0	0
	Total Rate of Energy Consumption (Wh/km)	262	262	263	265
Charge Sustaining	Rate of Electrical Consumption (Wh/km)	-88.24	-68.09	-63.17	-85.04
	Rate of Fuel Consumption (Wh/km)	1169	993	900	1214

	Fuel Tank Size (gal)	8	7	7	8
	Total Rate of Energy Consumption (Wh/km)	816	721	648	874
Energy Totals	**Vehicle Range (mi/km)**	194	193	190	185
	Fuel Consumption UF-Corrected (Wh/km)	256	226	306	271
	Fuel Consumption UF-Corrected (mpg)	57.79	65.47	48.41	54.6
	Electrical Consumption UF-Corrected (Wh/km)	180	180	135	183
	Energy Consumption UF-Corrected (Wh/km)	436	406	441	454
Emission Totals	**GHG WTP (g/km)**	84	84.4	61.5	85
	GHG PTW (g/km)	66.6	58.8	79.5	70.5
	GHG WTW (g/km)	150.6	143.3	141	155.6
	PEU WTW (Wh PE/km)	76.2	67.9	88.3	80.4

Table 12 : Performance Results

Specification	**Series -TV-A**	**Series -TV-B**	**Series-TV- C**	**Series-AWD**	**Units**
Acceleration, IVM-60 mph	5.3	5.3	5.7	5.6	sec
Acceleration, 50-70 mph (Passing)	2.9	2.9	3.2	2.7	sec
Highway Gradebility, @ 20 min	6% @ 60 mph	6% @ 60 mph	6% @ 60 mph	6% @ 60 mph	% Grade @ mph
Total Vehicle Range	312	310	305	298	km
CD Mode Range	49.57 (pure EV)	49.57 (pure EV)	49.02 (pure EV)	50.15 (pure EV)	mi

In Charge Depleting mode, the Series-TV-A and Series-TV-B have the lowest energy consumption. The Series-TV-C has the second lowest followed by the Series-AWD. The relatively higher energy consumption by the Series-TV-C and the Series-AWD is due to its relatively higher weight.

In Charge Sustaining mode, Series-TV-C with the better tuned engine the lowest energy consumption. The Series-TV-C for the same reasons has the lowest emissions. The Series TV-B has the second lowest energy consumption. Although the Series TV-A, Series TV-A, and the Series-AWD have the same engine, from the results the Series TV-B generator motor is more compatible.

The Series-TV-B has the lowest overall energy consumption, followed by the Series-TV-A. The large ESS of the Series-TV-A/B give them an edge over the Series-TV-C, which has a smaller ESS and hence a smaller CD range. The Series AWD with a more complex control strategy that optimizes the motor efficiency with variable torque requests and gearing would have probably yielded better results.

When it comes to performance, the Series-TV-A/Bs light weight and big ESS help them out perform the rest of the architectures in the 0-60mph test. The Series-AWD equipped with the 2-speed gear boxes help its motors be in their power band and hence has better 50-70mph acceleration. The Series-TV-C falls behind in performance because of its small ESS not being able to provide the power needed.

The Series-TV-B has the lowest total energy consumption and emissions, and the best performance. The Series-TV-B would be the best choice among the 4 models vehicle.

CONCLUSION

Modeling and Simulation of vehicles for Energy consumption, Emissions and Performance is only a part of the initial design process. Along with modeling and simulation, cost of components and ability to build the intended vehicle must be taken into consideration. Tradeoffs must be made to find the right balance between

More powerful and efficient components are generally more expensive. These components may improve you energy consumption, emissions and performance, but will be significantly more expensive to build. The right balance between cost and design specification must be met to make the vehicle desirable as well as affordable.

Vehicle based on their size and shape are classified into different tiers. The proposed vehicle must have components that can be packaged in the tier that the vehicle is designed for. The powertrain components need to be packaged such that there accessible to make the vehicle easily serviceable. Cost of a component is generally proportional to the power density of the component. The ability to package all the powertrain components in the vehicle while making them accessible is a challenge.

Although Series-TV-B may have the best design specification compared to the other tested vehicle, cost of components and the component packaging of this vehicle must be assessed before choosing this vehicle as the winner among the lot.

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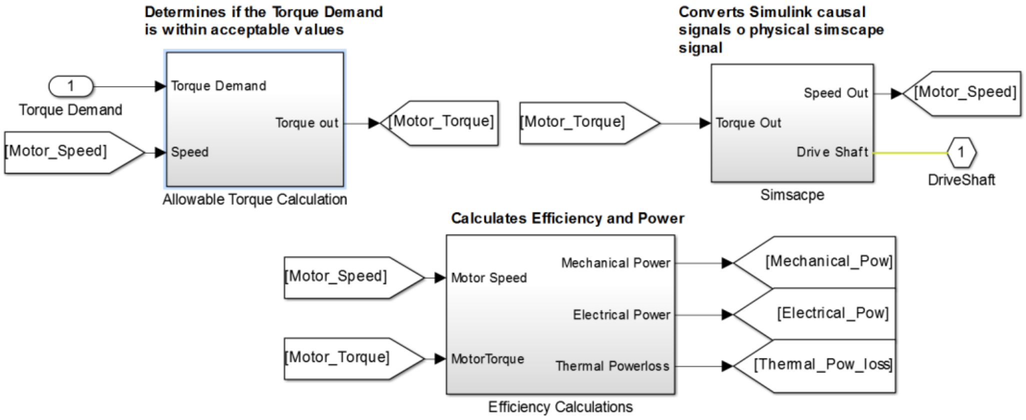
[7] Argonne National Laboratory, "ECOCAR 3 NON-YEAR-SPECIFIC RULES," Argonne National Laboratory, Chicago, 2014.

[8] Argonne National Labs, "GREET Model," Argonne National Labs, [Online]. Available: https://greet.es.anl.gov/main.

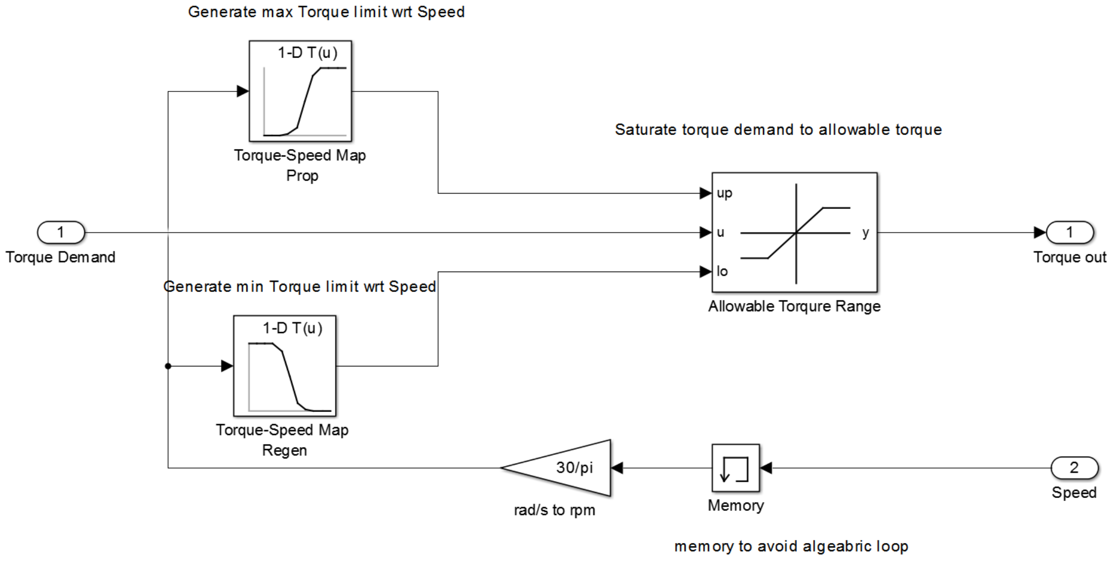
APPENDIX

Component modelling Example

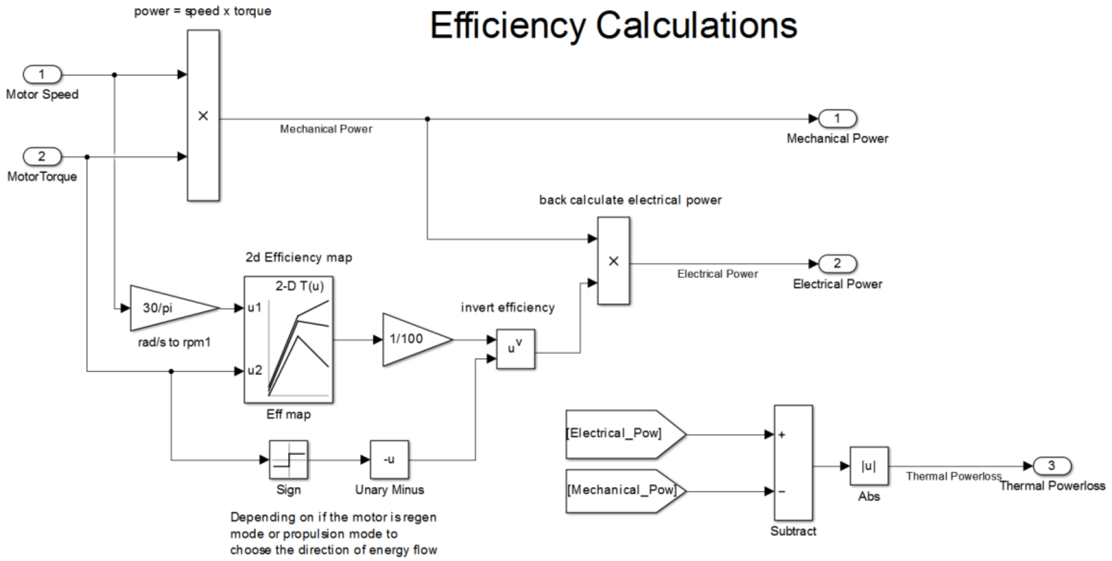
MOTOR Powerloss model

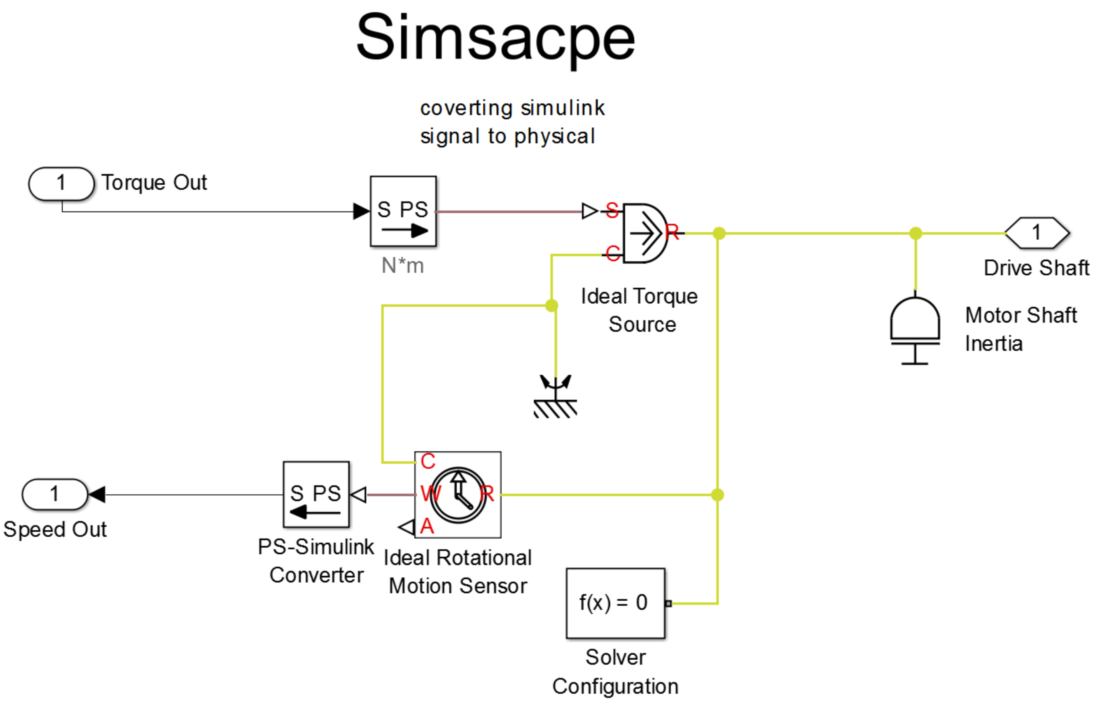


Allowable Torque Calculation

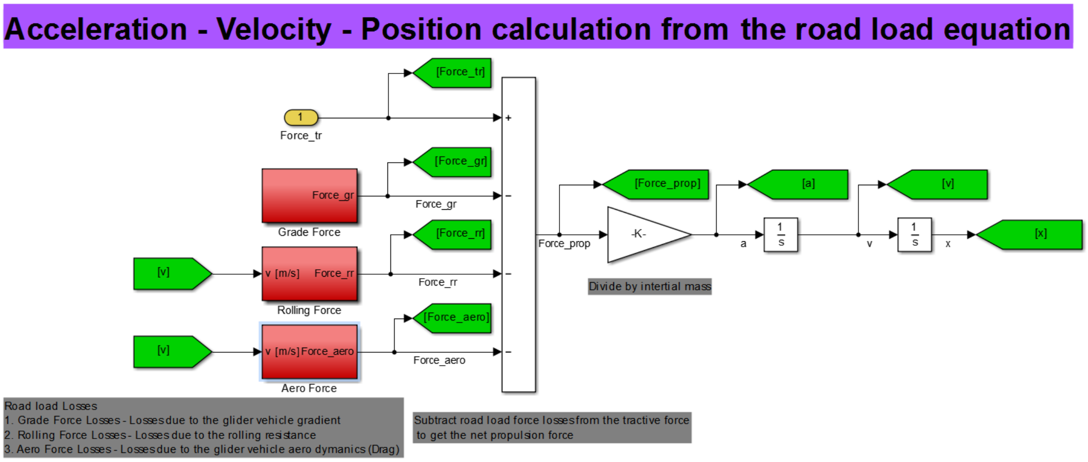


Efficiency Calculations





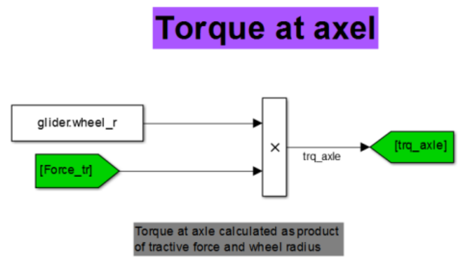
Vehicle Glider Model


Acceleration - Velocity - Position calculation from the road load equation

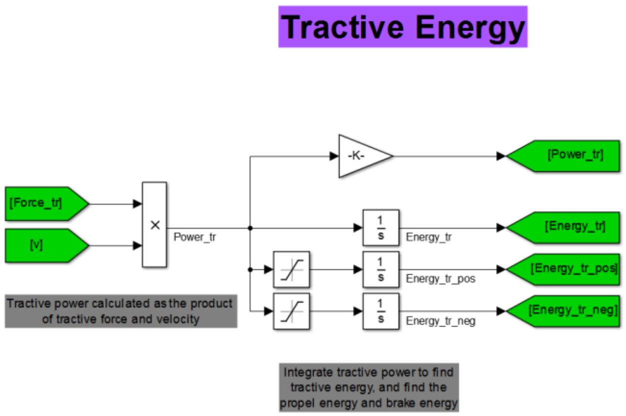
Divide by intertial mass

Road load Losses
1. Grade Force Losses - Losses due to the glider vehicle gradient
2. Rolling Force Losses - Losses due to the rolling resistance
3. Aero Force Losses - Losses due to the glider vehicle aero dymanics (Drag)

Subtract road load force losses from the tractive force
to get the net propulsion force

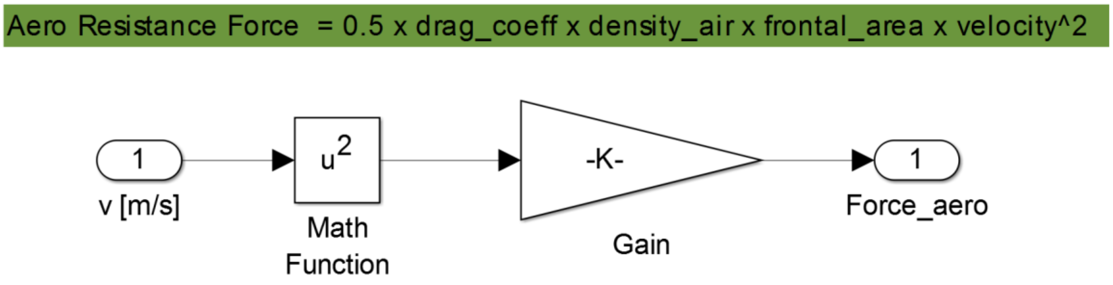


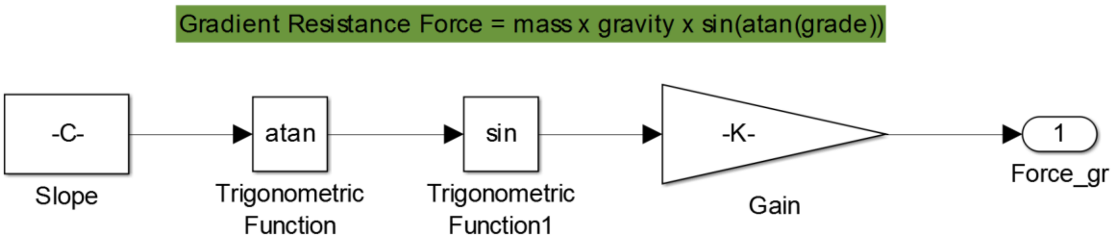
Torque at axle calculated as product of tractive force and wheel radius

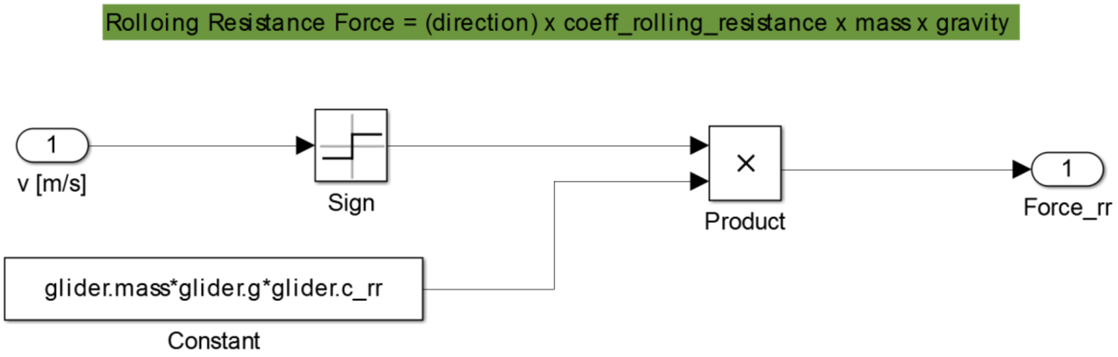


Tractive power calculated as the product of tractive force and velocity

Integrate tractive power to find tractive energy, and find the propel energy and brake energy


Aero Resistance Force = 0.5 x drag_coeff x density_air x frontal_area x velocity^2


Gradient Resistance Force = mass x gravity x sin(atan(grade))



Rolloing Resistance Force = (direction) x coeff_rolling_resistance x mass x gravity

MATLAB / Simulink model Layout

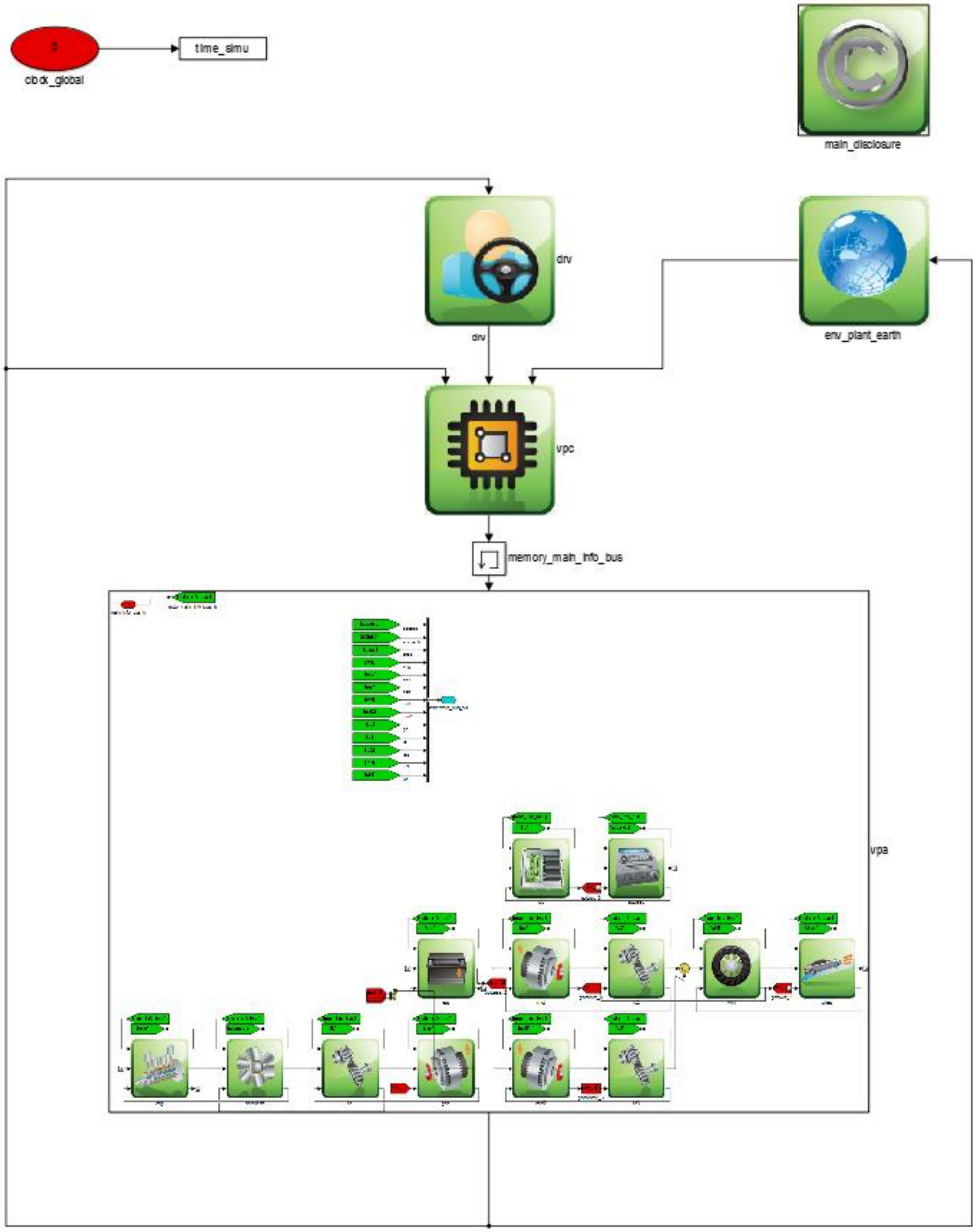


Figure 31 : Vehicle Model Layout in Autonomie

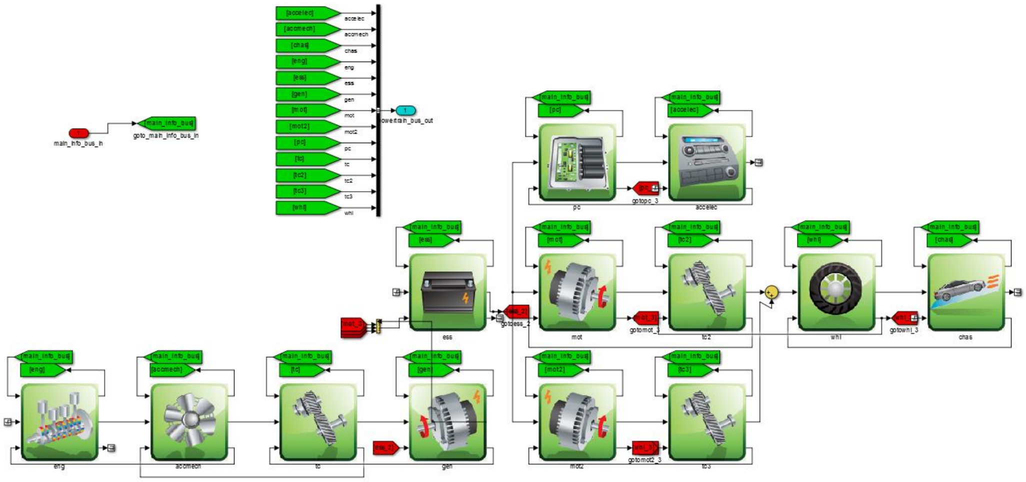
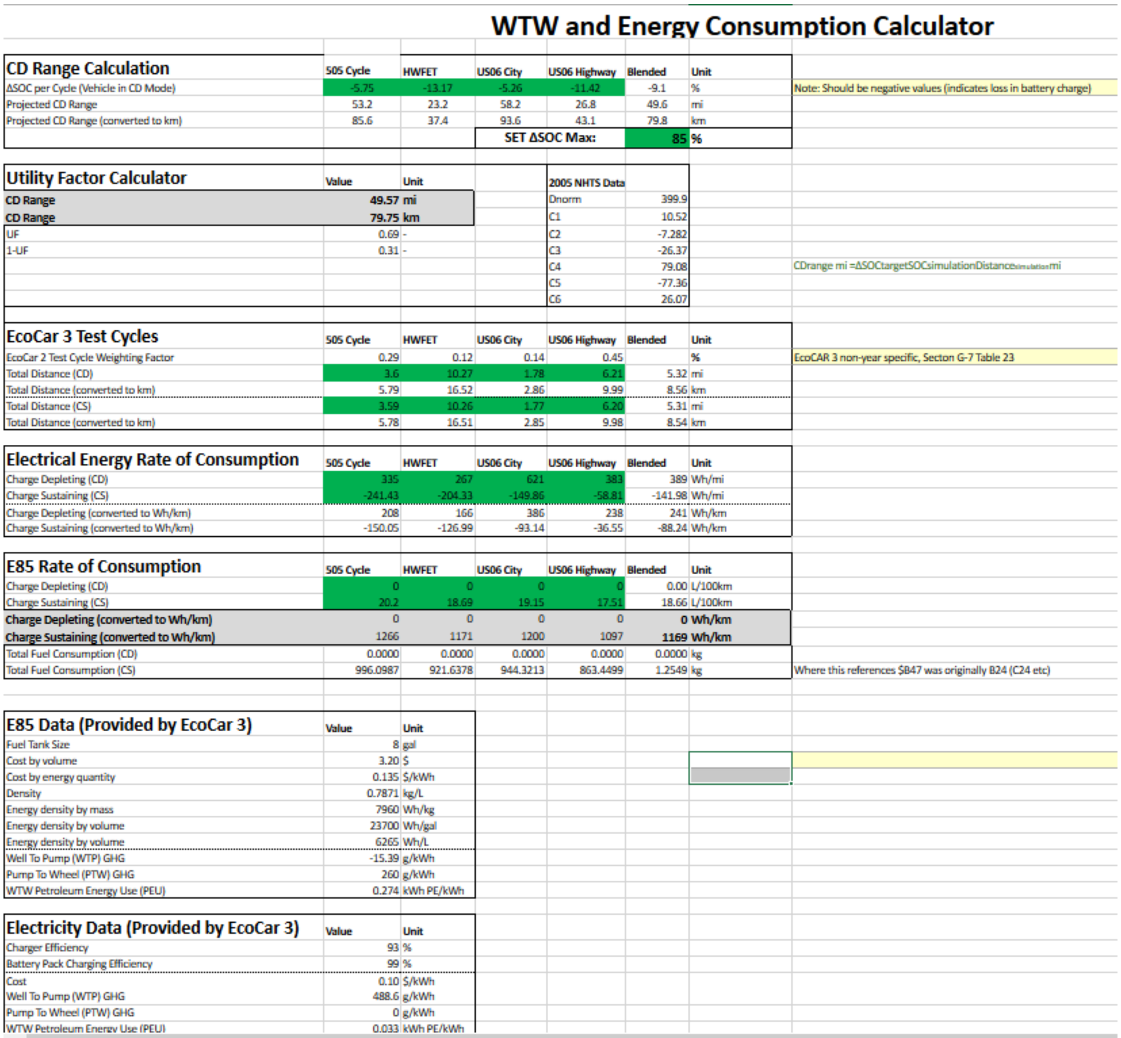


Figure 32 : Vehicle Component Model Layout in Autonomie



WTW and Energy Consumption Calculator

CD Range Calculation	505 Cycle	HWFET	US06 City	US06 Highway	Blended	Unit	
ΔSOC per Cycle (Vehicle in CD Mode)	-5.75	-13.17	-5.26	-11.42	-9.1	%	Note: Should be negative values (indicates loss in battery charge)
Projected CD Range	53.2	23.2	58.2	26.8	49.6	mi	
Projected CD Range (converted to km)	85.6	37.4	93.6	43.1	79.8	km	
			SET ΔSOC Max:		85	%	

Utility Factor Calculator	Value	Unit		2005 NHTS Data		
CD Range	**49.57**	**mi**		Dnorm	399.9	
CD Range	**79.75**	**km**		C1	10.52	
UF	0.69	-		C2	-7.282	
1-UF	0.31	-		C3	-26.37	
				C4	79.08	CDrange mi =ΔSOCtargetSOCsimulationDistancesimulationmi
				C5	-77.36	
				C6	26.07	

EcoCar 3 Test Cycles	505 Cycle	HWFET	US06 City	US06 Highway	Blended	Unit	
EcoCar 2 Test Cycle Weighting Factor	0.29	0.12	0.14	0.45		%	EcoCAR 3 non-year specific, Secton G-7 Table 23
Total Distance (CD)	3.6	10.27	1.78	6.21	5.32	mi	
Total Distance (converted to km)	5.79	16.52	2.86	9.99	8.56	km	
Total Distance (CS)	3.59	10.26	1.77	6.20	5.31	mi	
Total Distance (converted to km)	5.78	16.51	2.85	9.98	8.54	km	

Electrical Energy Rate of Consumption	505 Cycle	HWFET	US06 City	US06 Highway	Blended	Unit
Charge Depleting (CD)	335	267	621	383	389	Wh/mi
Charge Sustaining (CS)	-241.43	-204.33	-149.86	-58.81	-141.98	Wh/mi
Charge Depleting (converted to Wh/km)	208	166	386	238	241	Wh/km
Charge Sustaining (converted to Wh/km)	-150.05	-126.99	-93.14	-36.55	-88.24	Wh/km

E85 Rate of Consumption	505 Cycle	HWFET	US06 City	US06 Highway	Blended	Unit	
Charge Depleting (CD)	0	0	0	0	0.00	L/100km	
Charge Sustaining (CS)	20.2	18.69	19.15	17.51	18.66	L/100km	
Charge Depleting (converted to Wh/km)	0	0	0	0	**0**	**Wh/km**	
Charge Sustaining (converted to Wh/km)	1266	1171	1200	1097	**1169**	**Wh/km**	
Total Fuel Consumption (CD)	0.0000	0.0000	0.0000	0.0000	0.0000	kg	
Total Fuel Consumption (CS)	996.0987	921.6378	944.3213	863.4499	1.2549	kg	Where this references $B47 was originally B24 (C24 etc)

E85 Data (Provided by EcoCar 3)	Value	Unit
Fuel Tank Size	8	gal
Cost by volume	3.20	$
Cost by energy quantity	0.135	$/kWh
Density	0.7871	kg/L
Energy density by mass	7960	Wh/kg
Energy density by volume	23700	Wh/gal
Energy density by volume	6265	Wh/L
Well To Pump (WTP) GHG	-15.39	g/kWh
Pump To Wheel (PTW) GHG	260	g/kWh
WTW Petroleum Energy Use (PEU)	0.274	kWh PE/kWh

Electricity Data (Provided by EcoCar 3)	Value	Unit
Charger Efficiency	93	%
Battery Pack Charging Efficiency	99	%
Cost	0.10	$/kWh
Well To Pump (WTP) GHG	488.6	g/kWh
Pump To Wheel (PTW) GHG	0	g/kWh
WTW Petroleum Energy Use (PEU)	0.033	kWh PE/kWh

Figure 33 : Energy consumption and GREET Spreadsheet