ECE 595 Project 1 – Analysis of a Parallel Hybrid Electric Vehicle (HEV)

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Objective

The primary objectives of this project are to:

1. Simulate the performance of a mild parallel hybrid gas/electric vehicle using MATLAB and Simulink.
2. Analyze and discuss the results
3. Suggest and quantify improvements to the Power Management Strategy (PMS)

About the HEV

In this vehicle, an electric machine propels the vehicle at low speeds with the main engine disengaged. The electric machine is also used as a boost motor to improve high-speed accelerating characteristics. This permits a smaller internal combustion engine to be used without sacrificing overall performance. The relevant parameters used in this simulation are given in the tables in the next section.

Vehicular Parameters

No	Parameter	Symbol	Unit	Value
1	Vehicle Mass w/o battery, passengers or driver	M_{veh}	kg	1746
2	Wheel Radius	r_{wheel}	m	0.2794
3	Electric Machine Gear Ratio (Low)	$G_{elecmach}$	Unit less	1
4	Transmission Gear Ratio (Low)	$G_{trans, min}$	Unit less	0.3
5	Transmission Gear Ratio (High)	$G_{trans, max}$	Unit less	TBD
6	Differential Gear Ratio	G_{diff}	Unit less	0.25
7	Rolling Resistance Coefficient	C_0	Unit less	0.015
8	Aerodynamic Drag Coefficient	C_D	Unit less	0.35
9	Frontal Area	A_F	M^2	1.93
10	Battery Capacity	E_{batt}	kW-hr	TBD
11	Battery and Power Electronics Round-Trip Efficiency	$л_{batt}$	Unit less	0.7
12	Minimum Engine Power	$P_{eng, min}$	kW	10
13	Maximum Power	$P_{eng, max}$	kW	80
14	Initial SOC	SOC_{init}	Unit less	0.6
15	Density of Gasoline	N.A	kg/liter	0.75

Additional Parameters

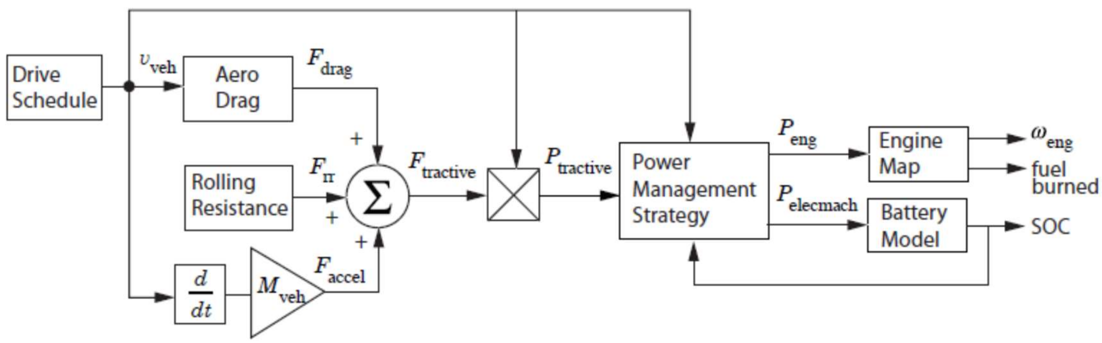
No	Parameter	Symbol	Unit	Value	Remarks
1	Air Density	p	Kg/m^3	1.225	Constant
2	Gravitational acceleration	g	m/s^2	9.807	Constant
3	Battery Mass	N.A	kg	Variable	See Section – Battery Model
4	Driver Mass	N.A	kg	75	Average weight of an American Male
5	Total Vehicular Mass (Mass of Vehicle + Battery + Driver)	N.A	kg	Variable	

Parameters to be derived/calculated

No	Parameter	Symbol	Unit	Calculation
1	Tractive Force	F_tractive	N	F_tractive = F_drag + F_rr + F_accel
2	Tractive Power	P_tractive	kW	P_tractive = F_tractive * V_veh
3	Engine Power	P_eng	kW	See section on PMS
4	Engine Speed	W_eng	rpm	See section on Engine Map
5	Electric Engine Power	P_elecmach	kW	See section on PMS
6	Electric Engine Speed	W_elecmach	rpm	See section on Electric Engine
7	Electric Engine Torque	T_elecmach	Nm	See section on Electric Engine
8	Battery State of Charge	SOC	Unit less	See section on Battery Model
9	Fuel burned/used	Gallons	gal	See Section on Engine Map
10	Fuel Efficiency	mpg	mpg	See Section on Efficiency Calculator

Simulation Block Diagram

The basic simulation block diagram is given below:



Sub-systems

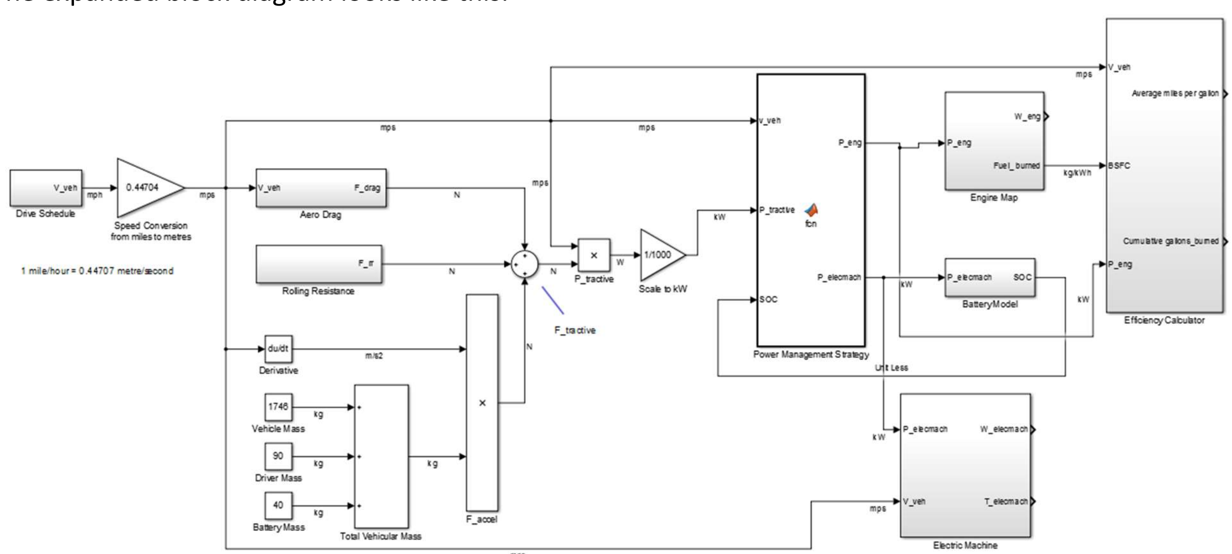
The following items from the basic are modelled as subsystems in Simulink.

- Drive Schedule
- Aero Drag
- Rolling Resistance
- Power Management Strategy
- Engine Map
- Battery Model

For the purpose of this project, two additional subsystems below are modelled:

- Efficiency Calculator
- Electric Machine

The expanded block diagram looks like this:



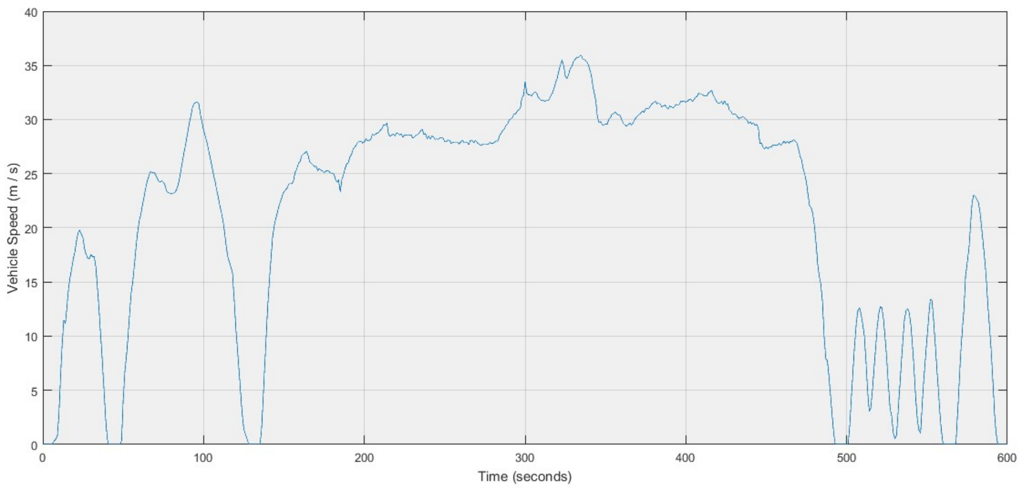
Drive Schedule

A drive schedule, also known as a driving cycle is a series of data points representing the speed of a vehicle versus time.

The purpose of a drive schedule is to assess/evaluate the performance of vehicles under different driving conditions.

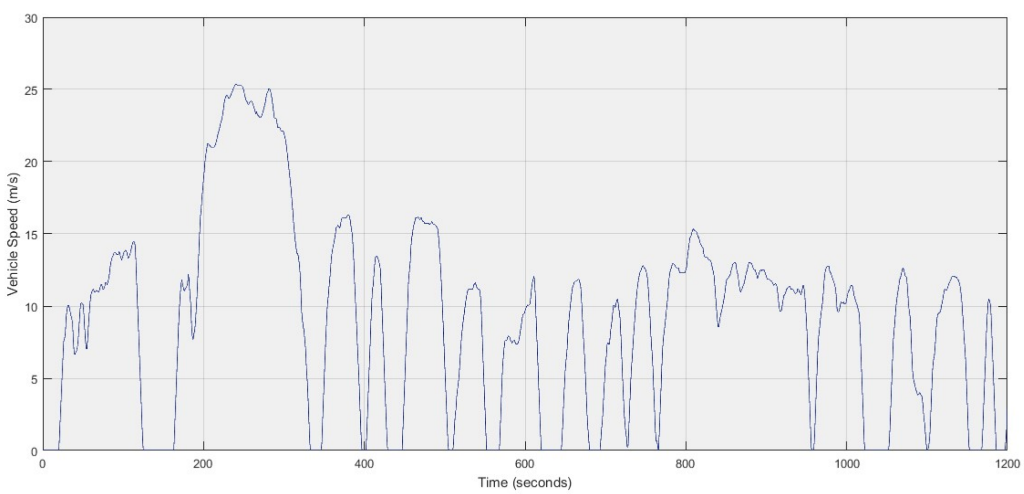
For the purpose of this simulation, we will be running the simulation with two different drive schedules:

- US06 Supplemental Federal Test Procedure (US06)
  - A representation of aggressive, high speed and/or high acceleration driving behavior, rapid speed fluctuations, and driving behavior following startup.



Graph of Vehicle Speed vs Time (US06)

- Urban Dynamometer Driving Schedule (UDDS)
  - A representation of city driving conditions



Aero Drag

The aerodynamic drag force (F_drag) is the viscous resistance of the air against the motion, and is calculated by the following equation:

$$F\_drag = 0.5 * p * C_D * A_F * (V\_veh)^2$$

where
p: Air Density
C_D: Aerodynamic Drag Coefficient
A_F: Frontal Area
v_veh: Vehicle Speed

Assumptions:

- Head-wind velocity = 0
- Vehicle Speed is always > 0

Simulink Notes:

- None

Rolling Resistance

The rolling resistance force can be understood as the force caused by the traction of the tires on the road surface.

$$F\_rr = M\_veh * g * C_0$$

where
M_veh: Total Vehicle Mass
G: Gravitational Acceleration
C_0: Rolling Resistance Coefficient

Assumptions:

- Vehicle Speed is always > 0
- F_rr is net for all four tires

Simulink Notes:

- None

Power Management Strategy (PMS)

The heart of this simulation is the Power Management Strategy (PMS) that is implemented in this project.

Given the required net tractive power P_tractive, the PMS determines the required power to be supplied by the main engine. The remainder is to be supplied by the electric machine (powered by the battery).

The main strategy is to maintain an average SOC of 0.6. In other words, the battery is used to provide boost power only in times needed, as opposed to providing a second power source to extend the vehicle range.

The following constraints are listed and implemented in MATLAB as a function:

Condition 1: If P_tractive (Tractive Power) < P_eng_min (Minimum Engine Power)

- Main Engine is disengaged => P_eng = 0
- Electric Engine will match tractive power => P_elecmach = P_tractive

Condition 2: If P_tractive (Tractive Power) > P_eng_max (Maximum Engine Power)

- Main Engine is fully engaged => P_eng = P_eng_max
- Electric Engine will supplement Main Engine => P_elecmach = P_tractive – P_eng_max

Condition 3: If P_eng_min < P_tractive < P_eng_max

- Battery is being recharged => P_elecmach =
  (-1)*(P_eng_max -P_tractive)*(0.6-SOC)
- Main Engine is engaged => P_eng = P_tractive - P_elecmach

Note that for condition 3, P_elecmach needs to be evaluated first.

Engine Map

The Engine Map illustrate the relationship between Engine Speed, Engine Power and the Brake Specific Fuel Consumption. The Engine Map for this simulation is provided:

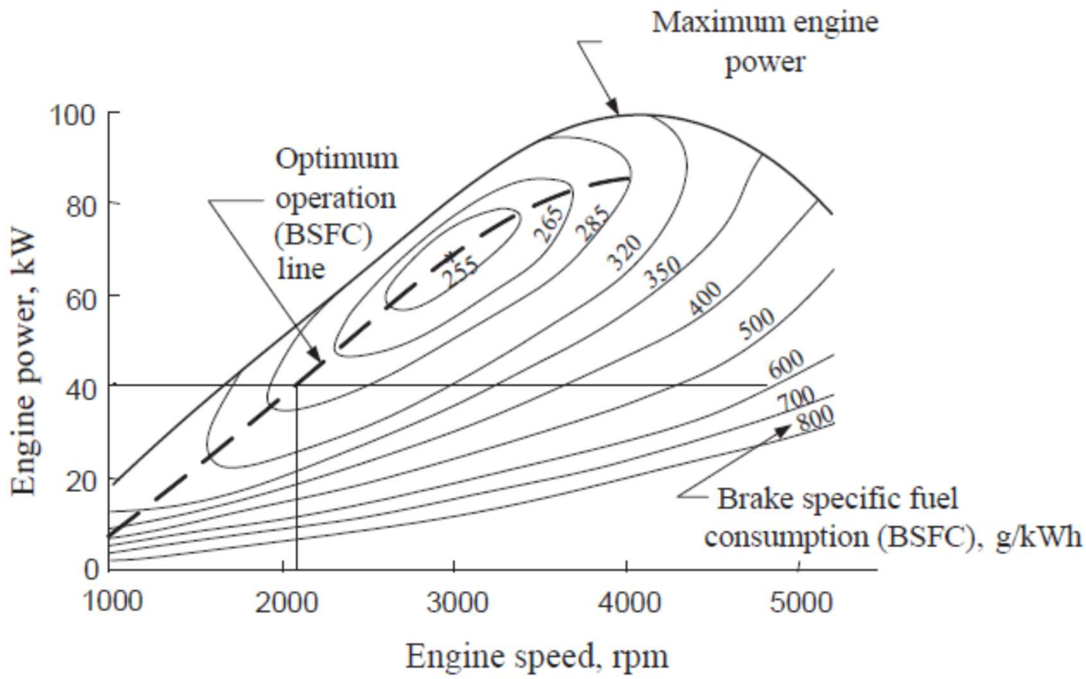


Figure 3: Engine map.

There is no need to calculate the equation of the optimum operation (BSFC) line as the values are given:

Table 3: Engine map

Speed (rpm)	Power (kW)	BSFC (g/kW-hr)
1009.3	7.66423	500
1183.18	12.7737	400
1588.89	24.635	320
1936.6	35.7664	285
2318.13	47.6277	265
2612.71	57.2993	255
3371.09	77.7372	255
3685.23	82.8467	265
4014	85.5839	285
4333.26	84.854	310
4657.51	81.0219	350
4919.09	72.8102	410
5108.24	62.0438	500

Assumptions:

- Whenever the main engine is engaged, its speed is assumed to be on the optimum BSFC line for the calculated engine power level.

Simulink Notes:

- Given P_eng (Engine Power), W_eng and Fuel_burned can be obtained respectively using 1-D lookup tables

Battery Model

One of the objective of this project is to select the battery capacity so that the SOC never exceeds 0.8 or falls below 0.4.

The target SOC is 0.6.

In our simulation model, the battery can be in three different states:

Condition 1: If P_elecmach > 0, Battery is discharging
- SOC will decrease

Condition 2: If P_elecmach < 0, Battery is charging
- SOC will increase

Condition 3: If P_elecmach = 0, Battery is idling (Not charging or discharging)
- SOC should hover around 0.6

Assumptions:

- Gravimetric Energy Density of the Battery = 46Wh/kg
- Battery and Power Electronics Round-Trip Efficiency = 0.7
- Initial SOC Condition = 0.6

Simulink Notes:

- Two switches are used to implement the logic of the battery charging and discharging

Selection Criteria:

To reach the target SOC, battery capacity of varying sizes are modelled.

The following Prius Battery Capacity is taken as the benchmark:

Weight :	1.05kg/module
No. of Modules:	38
Total Weight:	1.05 * 38 = 39.9 = 40 kg
Total Energy:	46 * 40 = 1840 Wh = 6,624,000 Ws = 6,624,000 J

Electric Machine

The electric machine is used to supplement the main engine when P_tractive is greater than the maximum engine power (80kW).

This subsystem utilizes P_elecmach and V_veh to calculate W_elecmach and T_elecmach.

$$V\_veh = r\_wheel * G\_diff * G\_elecmach * W\_elecmach$$

$$T\_elecmach = P\_elecmach / W\_elecmach$$

Assumptions:

- The Electric Machine is modelled only as an abstraction and is by no means representative of the actual vehicular architecture.

Simulink Notes:

- W_elecmach needs to be converted from rad/s to rps

Efficiency Calculator

The efficiency calculator is used to calculate the amount of fuel burned and the average miles travelled per gallon.

The amount of cumulative fuel burned can be calculated from the values of the BSFC and Engine Power.

Using the vehicle speed as a reference, the value for average miles per gallon can be derived from the amount of cumulative fuel burned.

Assumptions:

- N.A

Simulink Notes:

- BSFC is calculated in mass, and hence it needs to be converted to gallons

Results

The two drive schedules are loaded separately into the simulation.

The following variables are then calculated and plotted in MATLAB. They are sorted according to the order that they are first encountered.

The graphs are included in the appendices.

No	Variable	Symbol	Unit	Calculation	Reference
1	Tractive Force	F_tractive	N	F_tractive = F_drag + F_rr + F_accel	Figure A1, B1
2	Tractive Power	P_tractive	kW	P_tractive = F_tractive * V_veh	Figure A2, B2
3	Engine Power	P_eng	kW	See section on PMS	Figure A3, B3
4	Engine Speed	W_eng	rpm	See section on Engine Map	Figure A4, B4
5	Electric Engine Power	P_elecmach	kW	See section on PMS	Figure A5, B5
6	Electric Engine Speed	W_elecmach	rpm	See section on Electric Engine	Figure A6, B6
7	Electric Engine Torque	T_elecmach	Nm	See section on Electric Engine	Figure A7, B7
8	Battery State of Charge	SOC	Unit less	See section on Battery Model	Figure A8, B8
9	Fuel burned/used	Gallons	gal	See Section on Engine Map	Figure A9, B9
10	Fuel Efficiency	mpg	mpg	See Section on Efficiency Calculator	Figure A10, B10

Discussion and Analysis

As outlined in the first section, the primary objectives of this project are to simulate the performance of a mild parallel hybrid gas/electric vehicle using MATLAB and Simulink.

We shall first compare the performance of the vehicle over the two different drive schedules using the variables that were calculated and plotted.

No	Variable	Symbol	Unit	US06			UDDS		
				Max	Min	Mean	Max	Min	Mean
1	Tractive Force	F_tractive	N	7328	-5470	516.4	3101	-2492	334
2	Tractive Power	P_tractive	kW	103.4	-69.38	12.86	43.2	-31.47	3.45
3	Engine Power	P_eng	kW	80	0	15.78	43.89	0	3.77
4	Engine Speed	W_eng	rpm	3559	765.4	1298	2219	765.4	895
5	Electric Engine Power	P_elecmach	kW	23.4	-69.38	-2.91	9.99	-31.47	-0.32
6	Electric Engine Speed	W_elecmach	rpm	4908	0	2936	3465	0	1253
7	Electric Engine Torque	T_elecmach	Nm	511.4	-382	N.A	212.9	-174	N.A
8	Battery State of Charge	SOC	Unit less	0.73	0.59	0.64	0.61	0.52	0.57
				Total			**Total**		
9	Fuel burned/used	Gallons	gal	0.28			0.1567		
				Entire Schedule			**Entire Schedule**		
10	Fuel Efficiency	mpg	mpg	30			45		

General Observations

- The max, min and mean values of all variables for US06 are higher than those for UDDS.

Tractive Force & Power

- The tractive force experienced in US06 is generally higher due to the higher vehicle speed. The mean vehicle speed for US06 is 21.48 m/s while the mean speed for UDDS is only 9.19 m/s.

- As tractive power is a product of tractive force and vehicle speed, it is to be expected that the tractive power experienced in US06 is higher than that in UDDS.

Engine Power and Speed

- Again, the engine power and speed are translated from tractive power. Hence, the US06 drive schedule logs higher engine power and speed.

Electric Engine Power and Speed

- Here, it is observed that the mean of electric engine power for US06 is a negative number with a large magnitude than that of UDDS. Hence the SOC for US06 is expected to rise.
- The mean of electric engine power for UDDS is almost below, suggesting that the average rate of charge and discharge are very close to each other.

SOC

- Over its drive schedule, the SOC for US06 fluctuates, but did not fall below 0.6.
- Over its drive schedule, the SOC for UDDS fluctuates and eventually drops below 0.6.

Fuel Efficiency

- The fuel efficiency, or mpg for UDDS is better than that for US06. This is to be expected because the rapid speed fluctuations for US06 affects the fuel efficiency.

Suggested Improvements

Fuel Efficiency

- To improve the fuel efficiency or mpg, the power management strategy can be adjusted to maintain a lower SOC. This will allow the electric engine to supplement the internal combustion engine, hence reducing fuel consumption.

SOC

- To maintain an average SOC of 0.6, many different strategies can be employed. In this simulation, the battery can only be charged when the Tractive Power is between the minimum and maximum Engine Power. We can adjust the range for which the battery can be charged with respect to the drive schedule to achieve the desired SOC over a certain period of time.

Appendices

Appendix A – US06 Drive Schedule with a Simulation Time of 600

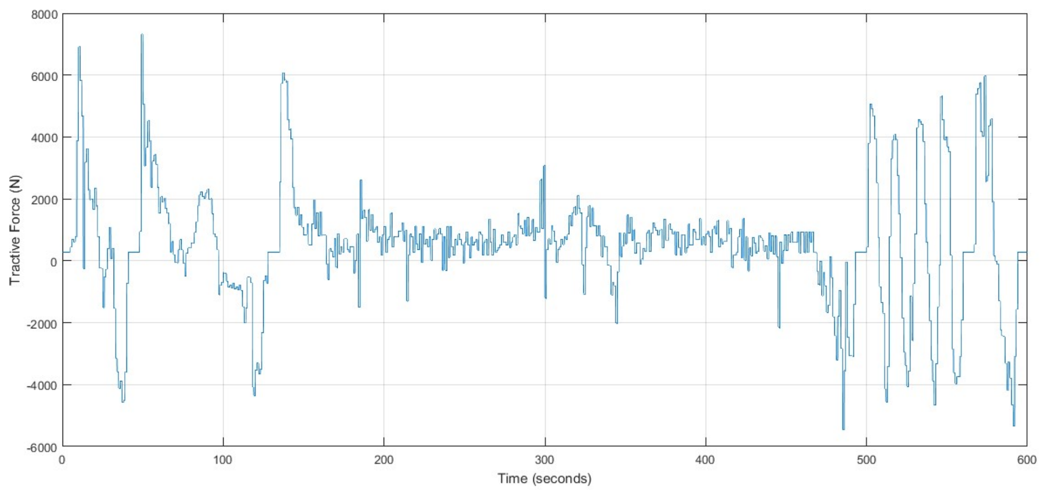


Figure A1 – Graph of Tractive Force vs Time

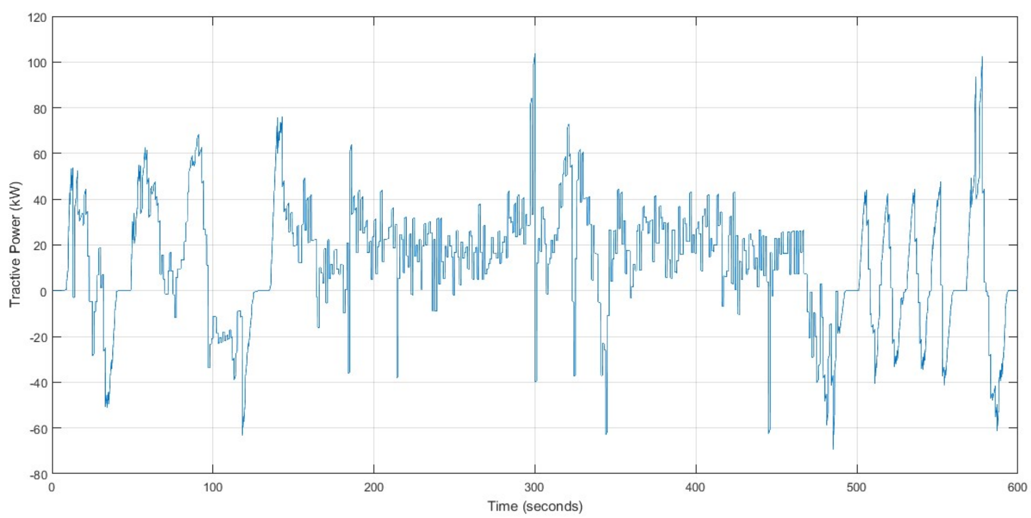


Figure A2 - Graph of Tractive Power vs Time

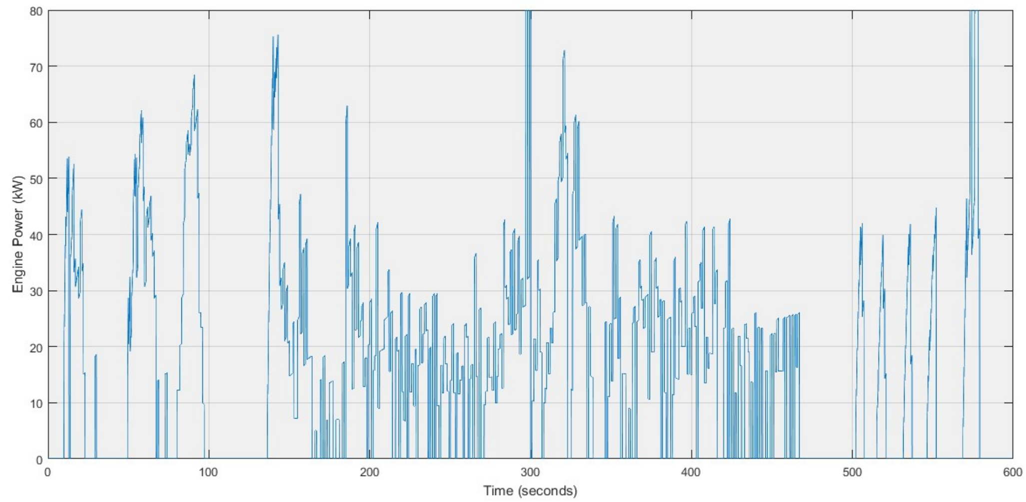


Figure A3 - Graph of Engine Power vs Time

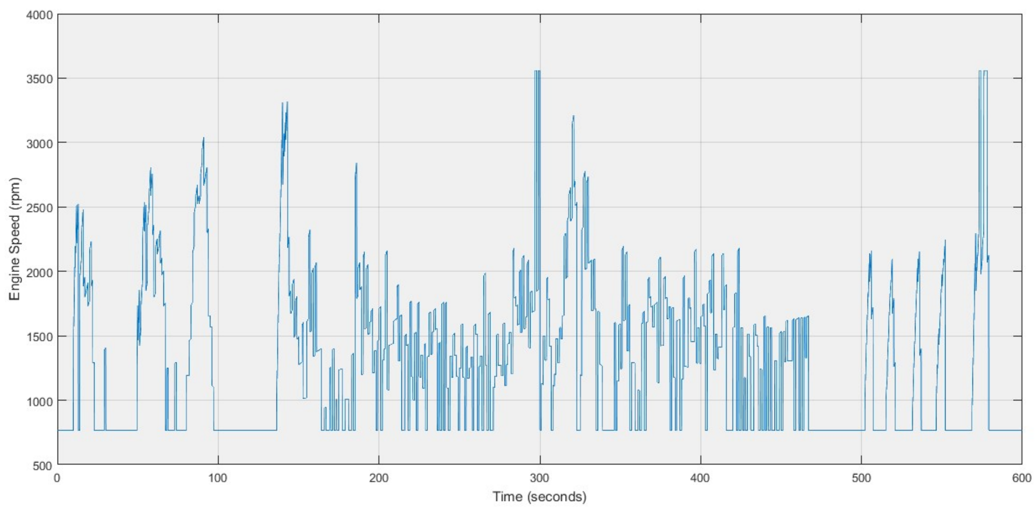


Figure A4 - Graph of Engine Speed vs Time

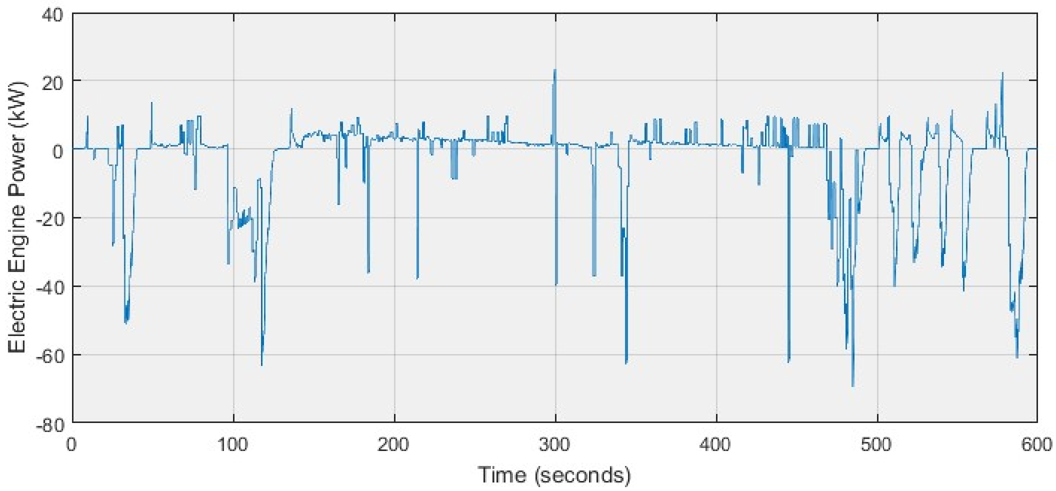


Figure A5 - Graph of Electric Engine Power vs Time

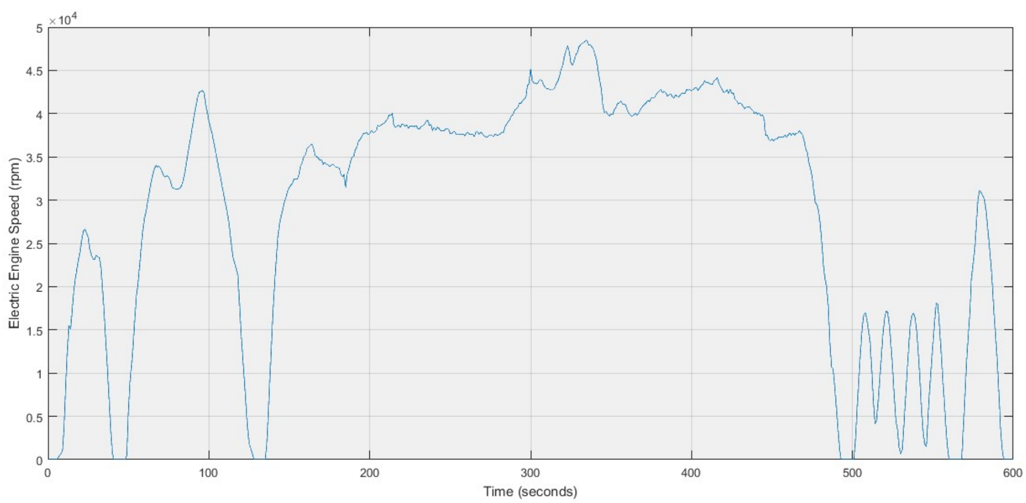


Figure A6 - Graph of Electric Engine Speed vs Time

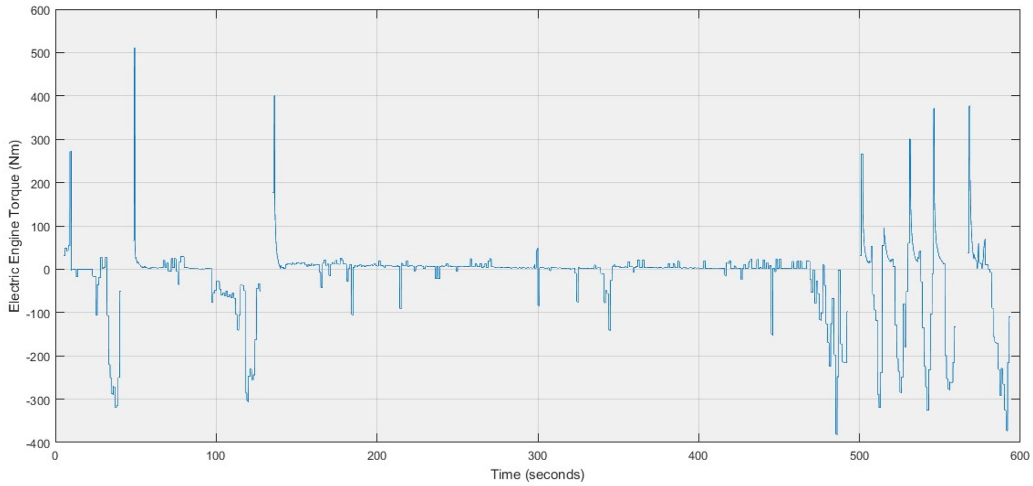


Figure A7 - Graph of Electric Engine Torque vs Time

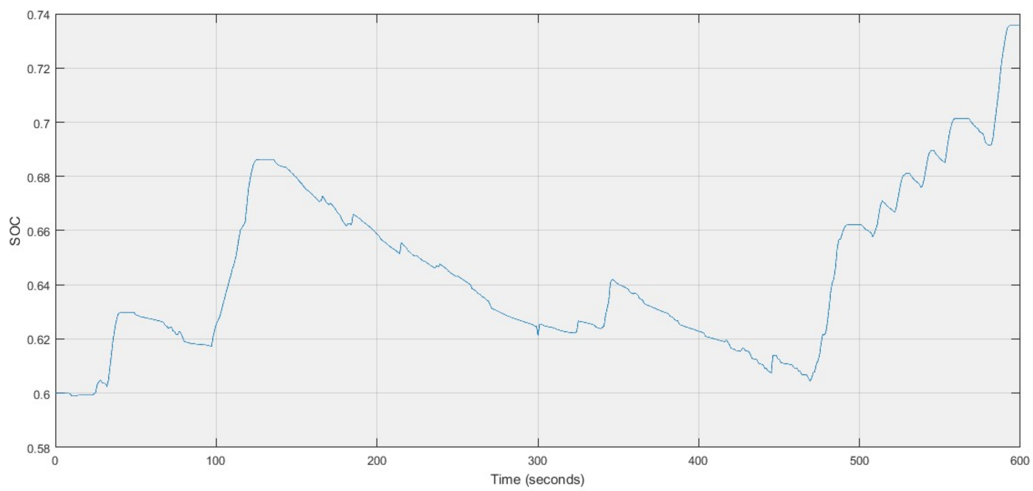


Figure A8 - Graph of SOC vs Time

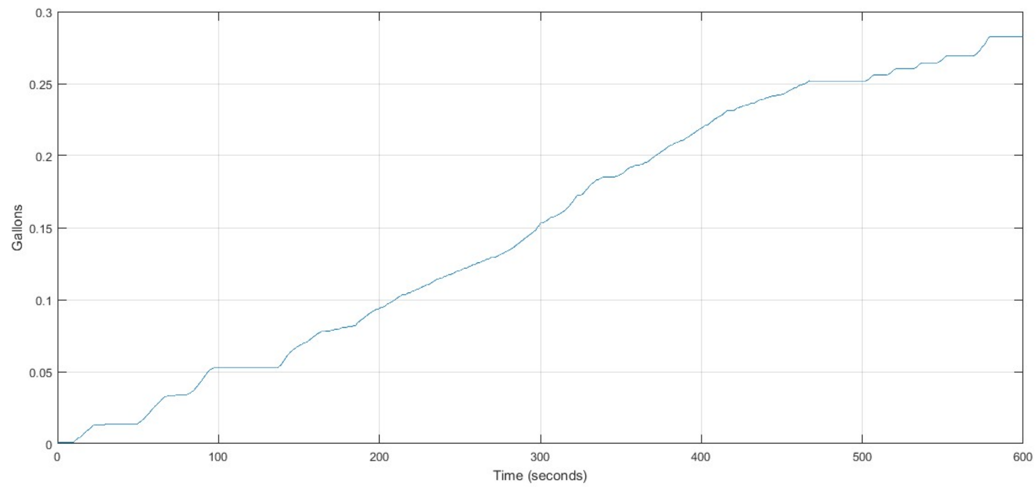


Figure A9 - Graph of Fuel Burned vs Time

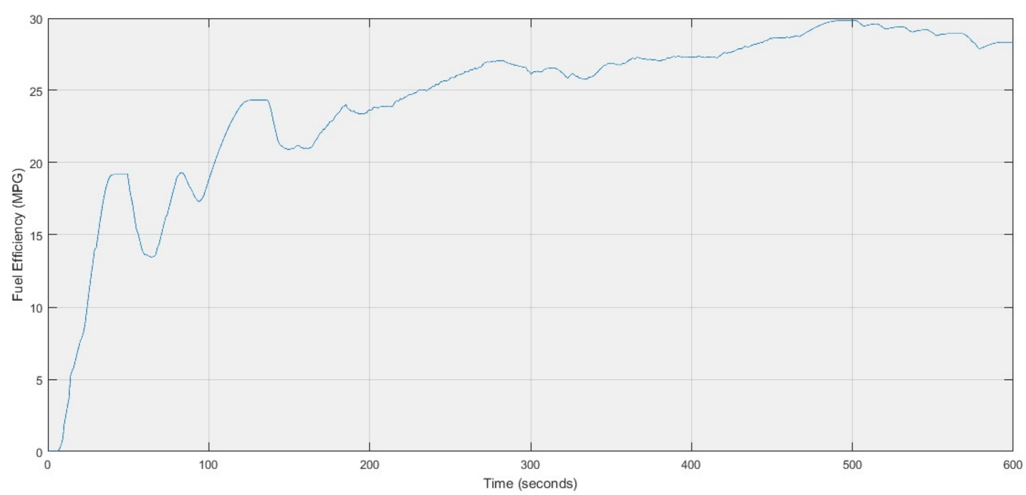


Figure A10 - Graph of MPG vs Time

Appendix B – UDDS Drive Schedule with a Simulation Time of 1200

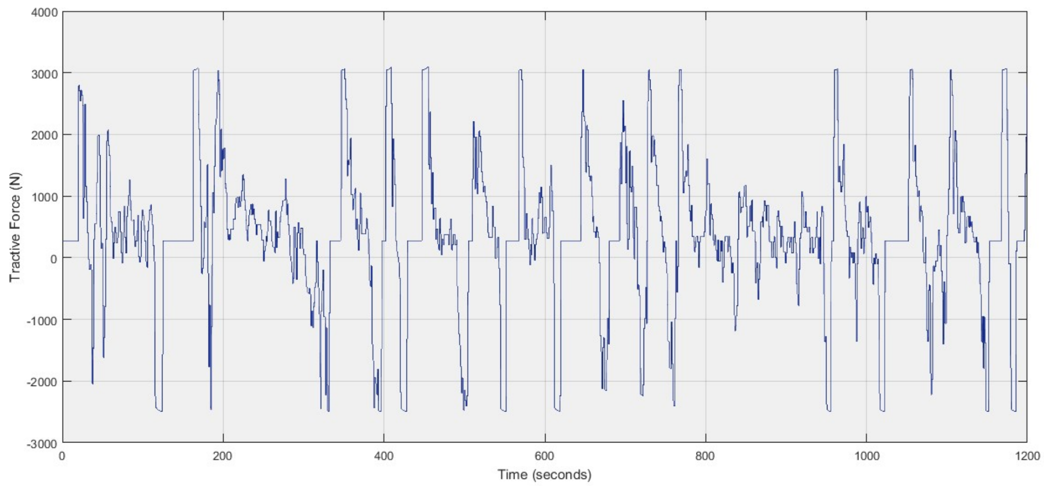


Figure B1 – Graph of Tractive Force vs Time

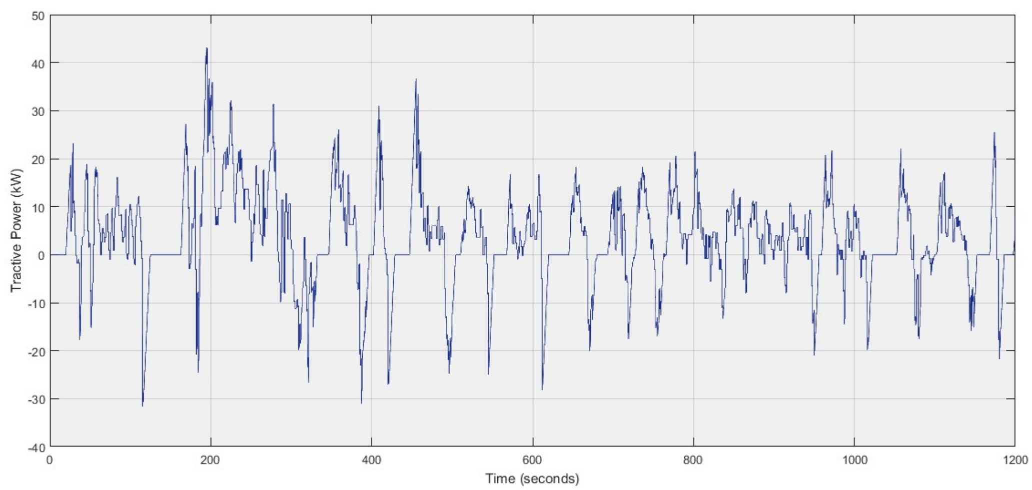


Figure B2 - Graph of Tractive Power vs Time

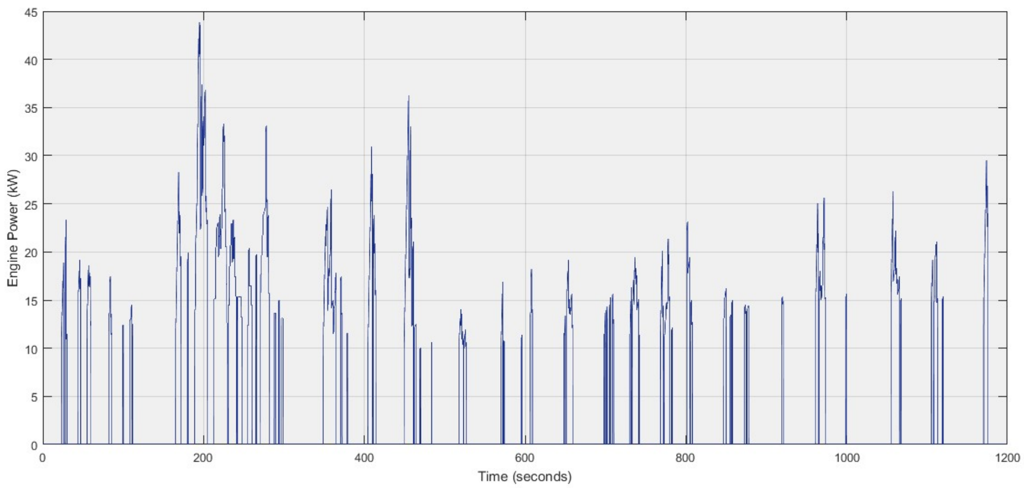


Figure B3 - Graph of Engine Power vs Time

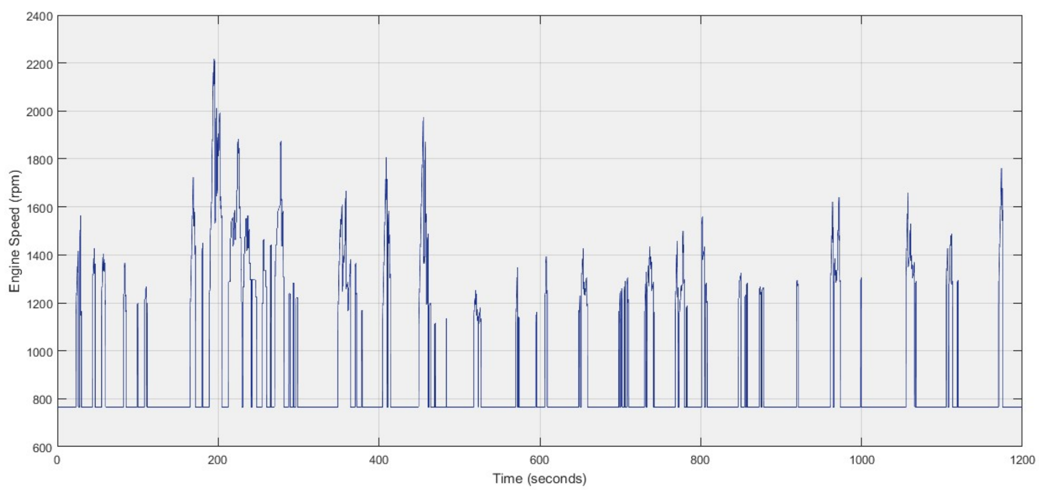


Figure B4 - Graph of Engine Speed vs Time

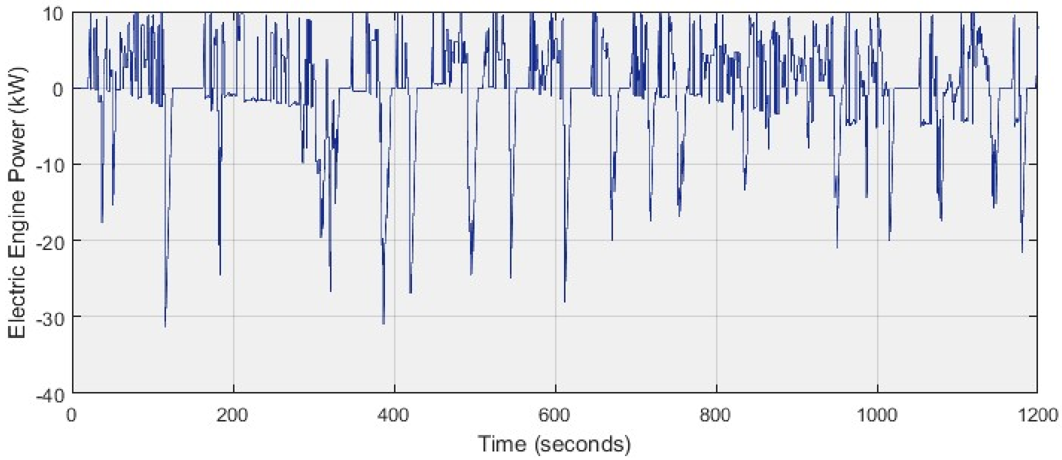


Figure B5 - Graph of Electric Engine Power vs Time

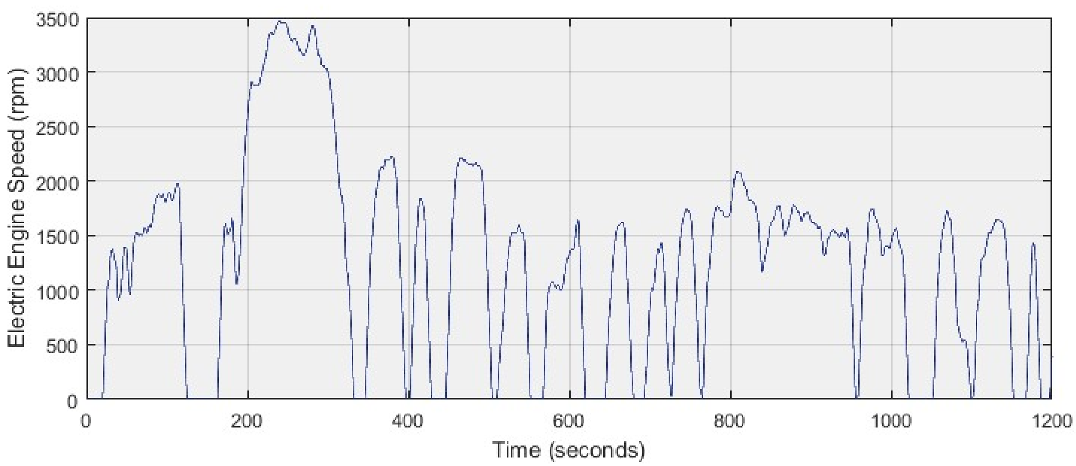


Figure B6 - Graph of Electric Engine Speed vs Time

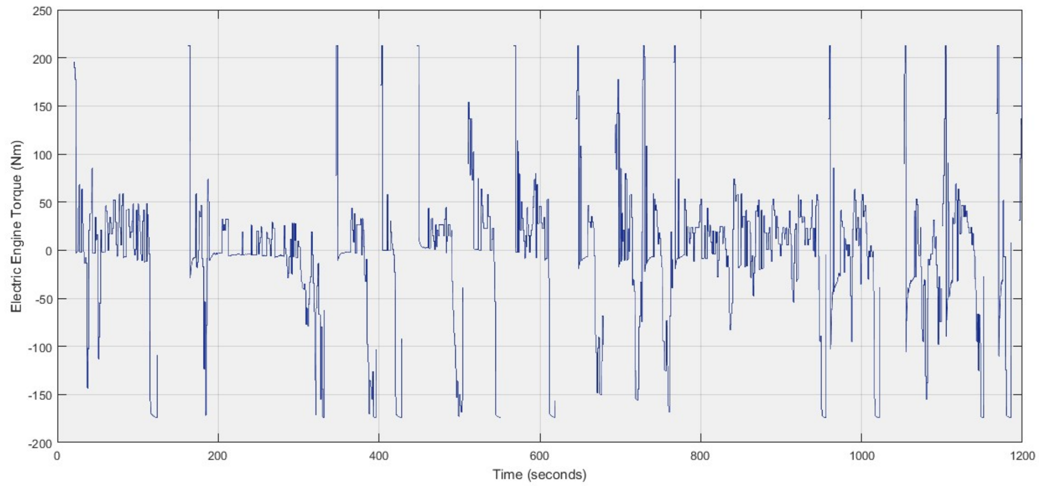


Figure B7 - Graph of Electric Engine Torque vs Time

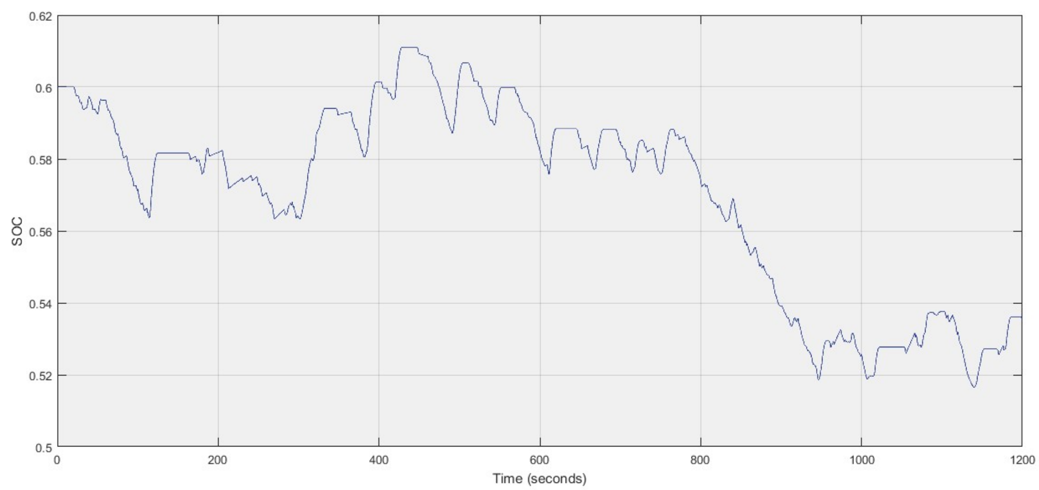


Figure B8 - Graph of SOC vs Time

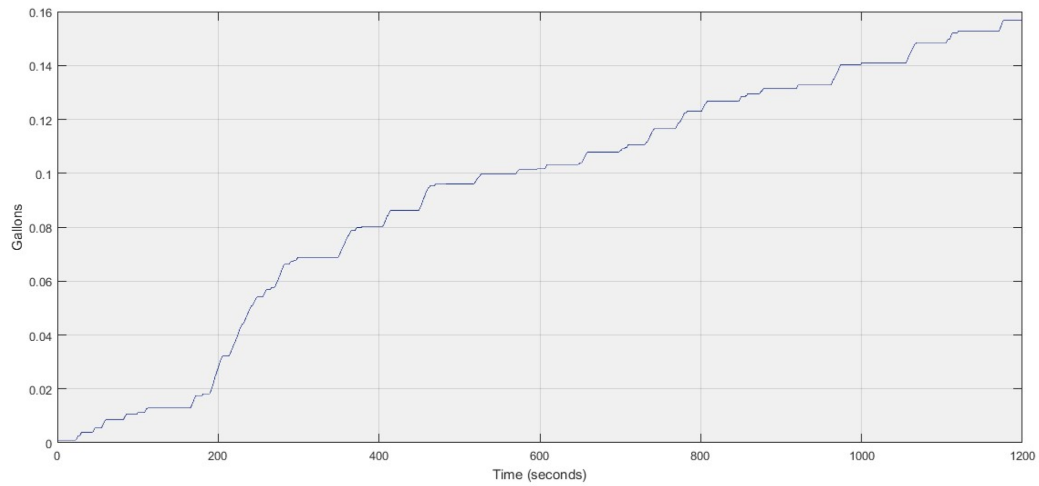


Figure B9 - Graph of Fuel Burned vs Time

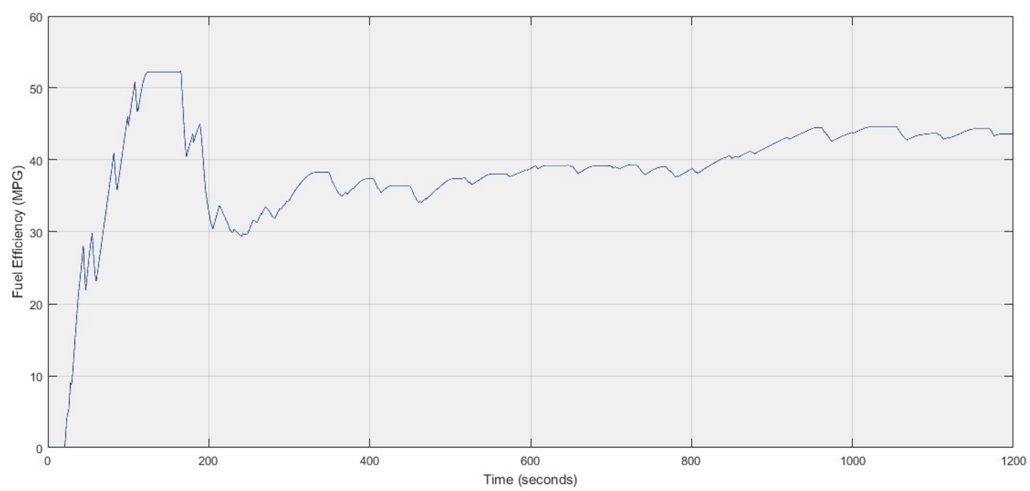


Figure B10 - Graph of MPG vs Time