Project Description:

The primary objective of the project is to analyze the performance of a mild parallel hybrid gas/electric vehicle. In this vehicle, an electric machine is to propel 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.

Following vehicle parameters are given:

Table 1: Vehicle parameters

Parameter	Symbol	Value
vehicle mass w/o battery, passengers, or driver	M_{veh}	1746 kg
wheel radius	r_{wheel}	0.2794 m
electric machine gear ratio	G_{elecmach}	1
transmission gear ratio (low)	$G_{\mathrm{trans,min}}$	0.3
transmission gear ratio (high)	$G_{\mathrm{trans,max}}$	TBD
differential gear ratio	G_{diff}	0.25
rolling resistance coefficient	C_0	0.015
aerodynamic drag coefficient	C_D	0.35
frontal area	A_F	1. m^2
energy storage subsystem capacity in kW-hr	E_{batt}	1.7
energy storage subsystem round-trip efficiency	η_{ess}	0.7
minimum engine power	$P_{\mathrm{eng,min}}$	10 kW
maximum engine power	$P_{\mathrm{eng,max}}$	80 kW
initial SOC	$\mathrm{SOC}_{\mathrm{init}}$	0.5
gravimetric density of gasoline	m_{gas}	0.75 kg/liter

Power management strategy is described in project documentation section.

Top level vehicle diagram should follow Fig 1a.

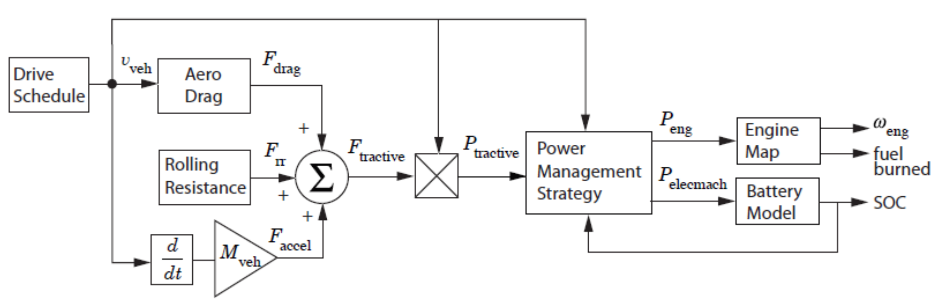

Fig 1a: Top level vehicle diagram

We have to:

1) Develop a Simulink model that accepts the driving schedule (US06 and LA92) as an input and calculates the power, torque, and speed of the engine and motor, as well as the battery state of charge (SOC) and fuel usage.
2) Select the battery capacity so that the SOC never exceeds 0.8 or falls below 0.2. The target SOC is 0.5. Assume a gravimetric energy density of 46 Wh/kg. Also, be sure to include own mass as the driver of the vehicle.
3) Calculate and plot the variables listed in Table 2.

Table 2: Variables to be plotted

Variable	Symbol	Unit
engine speed	ω_{eng}	rpm
engine power	P_{eng}	kW
electric machine power	P_{trans}	kW
electric machine speed	ω_{elecmach}	rpm
electric machine torque	T_{elecmach}	N-m
tractive force	T_{tractive}	N
tractive power	P_{tractive}	kW
battery state of charge	SOC	-

4) Calculate the fuel used, the average miles per gallon, and the SOC at the end of the drive cycle.
5) Based upon analysis of results, suggest improvements to given power management strategy. Quantify the improvement for both drive cycles.

Project Documentation:

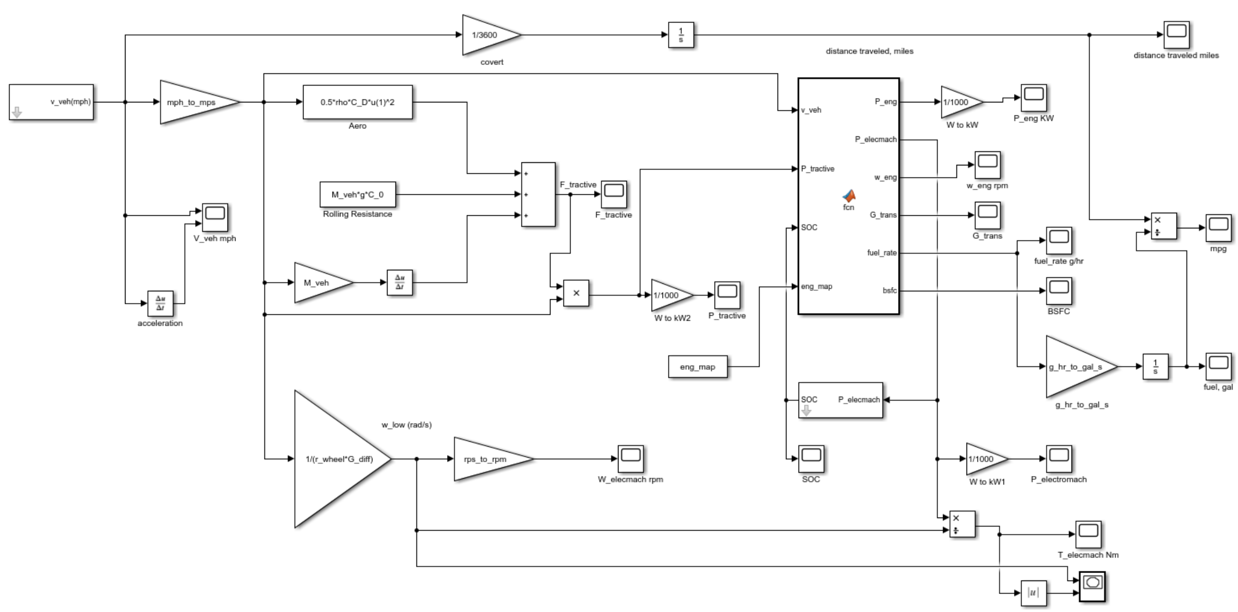

Fig 1b: Simulink model of the mild hybrid vehicle. ‘Proj1a.slx’ file.

Fig 1b is showing the Simulink model for mild hybrid vehicle. ‘init.m’ file contains all the values of the constants and conversions. It has to be run before running the Simulink model so that all the constants and conversions are in Matlab workspace. This file also loads the engine map file, US06 cycle file and

LA92 cycle file. Engine map and cycle files were provided in .txt format. Battery weight and passenger weight were added to vehicle weight.

Init.m file

```
E_max = 1.7*1000*3600; %J battery size
M_battery = E_max/46/3600; % battery weight in kg, based on Emax and 46 wh/kg battery energy density
M_passenger = 250; %passenger+driver weight, kg
M_veh = 1746 + M_passenger + M_battery;  % total vehicle weight, kg
C_D = 0.35;    % drag coefficient
C_0 = 0.015;   % rolling resistance coefficient
A_F = 1;    % frontal area, m^2
eta_ess = 0.7; % energy storage subsystem efficiency
r_wheel = 0.2794; % wheel radius, m
P_min_eng = 10000.0; % min engine power, W
P_max_eng = 80000.0; % max engine power, W

G_diff = 0.25;     % differential gear ratio
G_trans_min = 0.3; % minimum tansmission gear ratio

% unit conversions
m_to_mi = 1/1609; % meters to miles
g_hr_to_gal_s = 9.778e-8;  % g/hr to gal/s
mph_to_mps = 0.44704; % mi/hr to m/s
rps_to_rpm = 60/2/pi; %rad/sec to rpm

% physical constants
rho = 1.225; % density of air, kg/m^3
g = 9.8; % acceleration due to gravity,  m/s^s


SOC_init = 0.5; %initial SOC

load eng_map.txt
load us06.txt
load la92.txt
```

eng_map.txt is a text file which contains engine power and rpm according to optimum operation line.

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

Fig 1c: Engine map.

US06 drive cycle can be downloaded from: *https://www.epa.gov/sites/production/files/2015-10/us06col.txt*

LA92 drive cycle can be downloaded from: *https://www.epa.gov/sites/production/files/2015-10/la92dds.txt*

Simulink solver configuration was changed according to following figure:

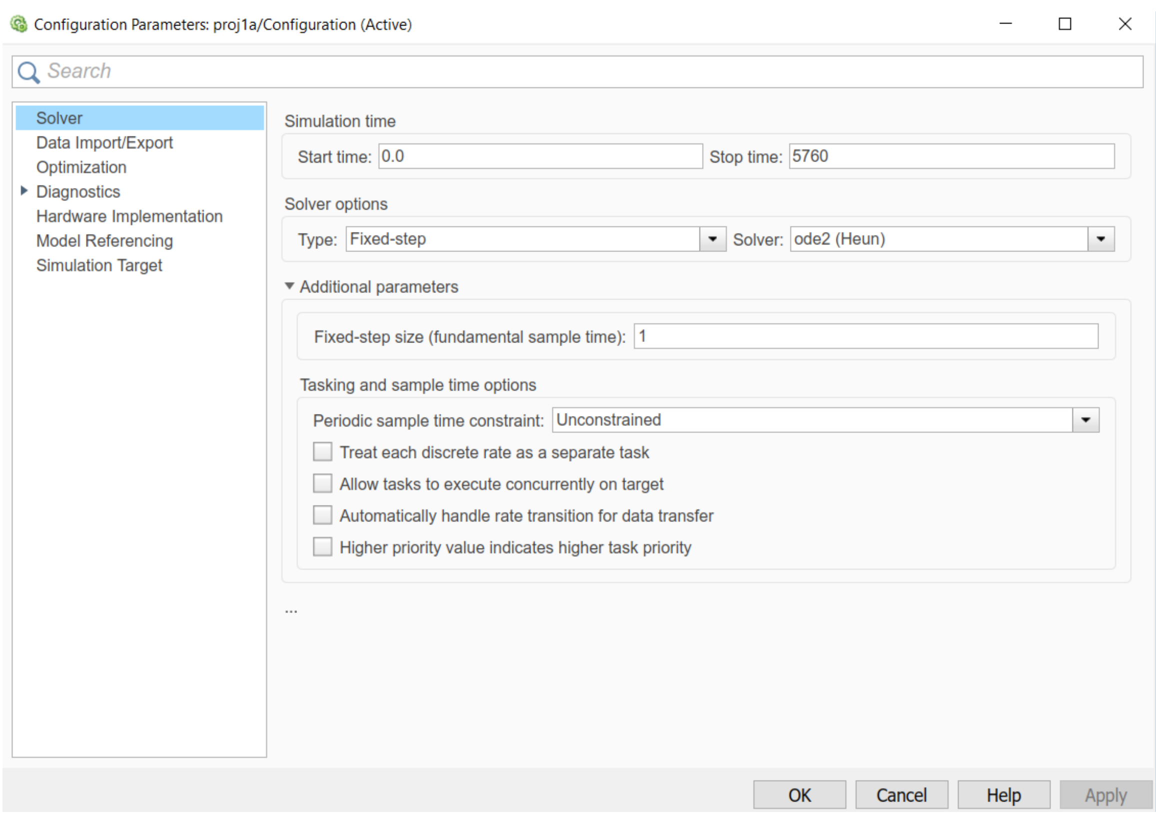

Fig 2: Simulink configuration parameter.

‘Matlab function’ block in Simulink model contains the power management strategy. All the .m, .slx and .txt files should be inside the same folder. That folder path should be added to ‘Matlab path’ before running the simulation.

Simulation time should be at least 3 times more than cycle time. US06 cycle is 600s long. So, simulation time should be 3*600 = 1800s or more. LA92 cycle is 1435s long.

To select appropriate drive cycle, ‘drive schedule’ should be changed between ‘la92’ and ‘us06’ in ‘Drive Cycle’ block at the Simulink model.

<u>Tractive Force and Power Calculation:</u>

$F_{tractive} = F_{rolling\_resistance} + F_{aero} + F_{acceleration}$, assuming grade = 0. (1)

$F_{rolling\_resistance} = M_{\_veh}*g*C_{\_0}$ (2)

$F_{aero} = 0.5*rho*A_{frontal} *C_{\_D}*v_{\_veh}$^2 (3)

$F_{acceleration} = M_{\_veh}*a_{\_veh}$ (4)

$P_{tractive} = F_{tractive}*v_{\_veh}$ (5)

<u>Motor Speed and Torque Calculation:</u>

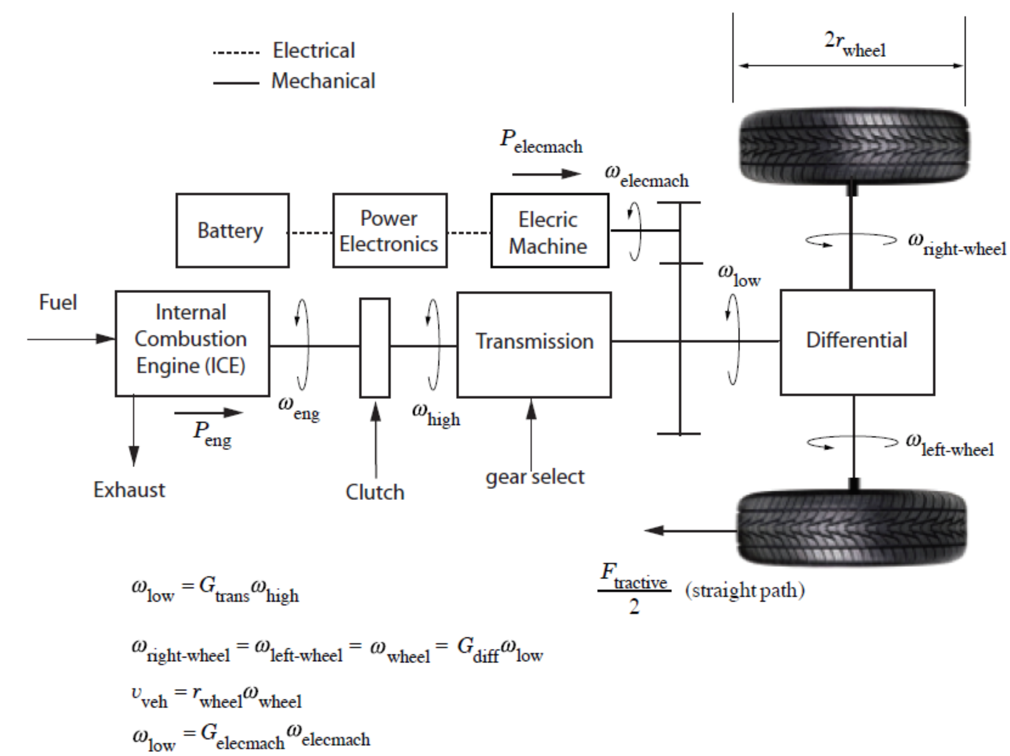

Fig 3: Mild parallel hybrid vehicle.

$\omega_{elecmach} = \omega_{low}/G_{elecmach} = \omega_{wheel}/(G_{elecmach} * G_{diff}) = v_{vehicle}/(r_{wheel} * G_{elecmach} * G_{diff})$ (6)

$T_{elecmach} = P_{elecmach}/\omega_{elecmach}$ (7)

Matlab Function Block (Power Management Strategy):

Inputs of this block are v_veh, P_tractive, SOC, eng_map. 'eng_map' file contains the optimum BSFC values based on engine rpm and engine power on a table format. Outputs of this function are P_eng, P_elecmach, w_eng, G_trans and fuel_rate based on the following strategy:

Given the required net tractive power Ptractive, the power manager determines how much of the required power is to be supplied by the engine. The remainder is to be supplied by the electric machine. The strategy is to maintain an average SOC of 0.5. That is, 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. Other operating strategies/constraints are listed below:

1. If Ptractive is less than minimum engine power (10 kW), the engine is disengaged (Peng = 0) and that a positive Ptractive is supplied by the electric machine (making it a motor) while a negative Ptractive means that mechanical power is supplied to the electric machine (making it a generator). The latter case is known as regenerative braking.

```
if(P_tractive < P_min)   % low-tractive-power, turn engine off
P_elecmach = P_tractive;
fuel_rate = 0;
w_eng = 0;
P_eng = 0;
G_trans = G_trans_min;
```

2. If Ptractive is greater than maximum engine power (80 kW), assume Peng = Peng;max and that Pelecmach = Ptractive - Peng;max

```
if(P_tractive > P_max) %high-speed boost
  P_elecmach = P_tractive-P_max;
  P_eng = P_max;
  bsfc = interp1(eng_map(:,2), eng_map(:,3), P_eng/1000);
  fuel_rate = bsfc*P_eng/1000; % g/hr
  w_eng = interp1(eng_map(:,2), eng_map(:,1), P_eng/1000);
  w_rad_p_s = w_eng*pi/30; % convert to rad/s
  G_trans =  v_veh/r_wheel/G_diff/w_rad_p_s;
```

3. The engine is assumed disengaged (Peng = 0) if its speed ωeng is below minimum. This occurs at low vehicle speeds and the transmission operating at its lowest gear ratio Gtrans;min.

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

5. Whenever Peng;min < Ptractive < Peng;max, the excess engine capacity is used to recharge the battery. Initially, we will try Pelecmach = -(Peng;max - Ptractive)(0.5 - SOC) and Peng = Ptractive - Pelecmach.

```
% charge sustaining mode
P_elecmach = -(P_max-P_tractive)*(0.5-SOC);
P_eng = P_tractive-P_elecmach;
bsfc = interp1(eng_map(:,2), eng_map(:,3), P_eng/1000);
fuel_rate = bsfc*P_eng/1000; % g/hr

w_eng = interp1(eng_map(:,2), eng_map(:,1), P_eng/1000);
w_rad_p_s = w_eng*pi/30;  % convert to rad/s
G_trans =  v_veh/r_wheel/G_diff/w_rad_p_s;
```

Complete code of the 'Matlab Function' block:

```
function [P_eng, P_elecmach, w_eng, G_trans, fuel_rate, bsfc] = fcn(v_veh, P_tractive, SOC, eng_map)
%#codegen

v_min = 2.19;  % minimum vehicle speed for engine to stay engaged, in m/s
P_min = 10000; % minimum engine power in W
P_max = 80000; % maximum engine power
G_trans_min = 0.3; % minimum transmission gear ratio
G_diff = 0.25;    % differential gear ratio
r_wheel = 0.2794; % wheel radius in m


bsfc = 0;
if (v_veh < v_min)  % low-speed acceleration
  P_elecmach = P_tractive;
  P_eng = 0;
  fuel_rate = 0;
  w_eng = 0;
  G_trans = G_trans_min;
  return

end

if(P_tractive < P_min)   % low-tractive-power, turn engine off
  P_elecmach = P_tractive;
  fuel_rate = 0;
  w_eng = 0;
  P_eng = 0;
  G_trans = G_trans_min;
  return
```

```
end

if(P_tractive > P_max) %high-speed boost
  P_elecmach = P_tractive-P_max;
  P_eng = P_max;
  bsfc = interp1(eng_map(:,2), eng_map(:,3), P_eng/1000);
  fuel_rate = bsfc*P_eng/1000; % g/hr
  w_eng = interp1(eng_map(:,2), eng_map(:,1), P_eng/1000);
  w_rad_p_s = w_eng*pi/30; % convert to rad/s
  G_trans =  v_veh/r_wheel/G_diff/w_rad_p_s;
  return
end
% charge sustaining mode
P_elecmach = -(P_max-P_tractive)*(0.5-SOC);
P_eng = P_tractive-P_elecmach;
bsfc = interp1(eng_map(:,2), eng_map(:,3), P_eng/1000);
fuel_rate = bsfc*P_eng/1000; % g/hr

w_eng = interp1(eng_map(:,2), eng_map(:,1), P_eng/1000);
w_rad_p_s = w_eng*pi/30;  % convert to rad/s
G_trans =  v_veh/r_wheel/G_diff/w_rad_p_s;

if(P_eng<P_min) % shut it off
  P_eng = 0;
  P_elecmach = P_tractive;
  fuel_rate = 0;
  w_eng = 0;
  G_trans = G_trans_min;
  return
end
```

ESS subsystem block (SOC calculation):

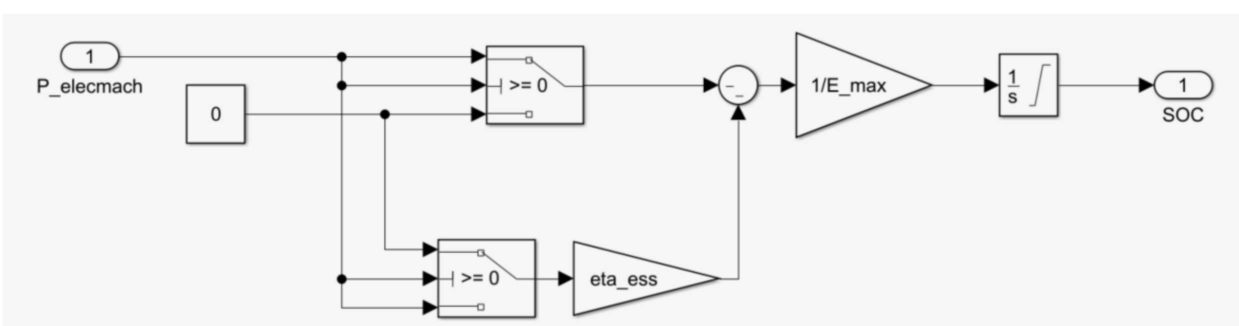

Fig 3.a: Energy subsystem. Calculating SOC from motor power.

If P_elecmach is greater than zero then it goes through the top switch. If P_elecmach is smaller than zero, then it goes through the bottom switch. The output of this block is the energy drawing from battery/using to recharge battery. Dividing the energy by E_max and then integrating it gives us SOC. Now the output is first divided by E_max and then integrated because it helps to initialize the integrator block between 0 and 1.

Results for cycle US06

The cycle represents an 8.01 mile (12.8 km)

average speed of 48.4 miles/h (77.9 km/h)

maximum speed 80.3 miles/h (129.2 km/h)

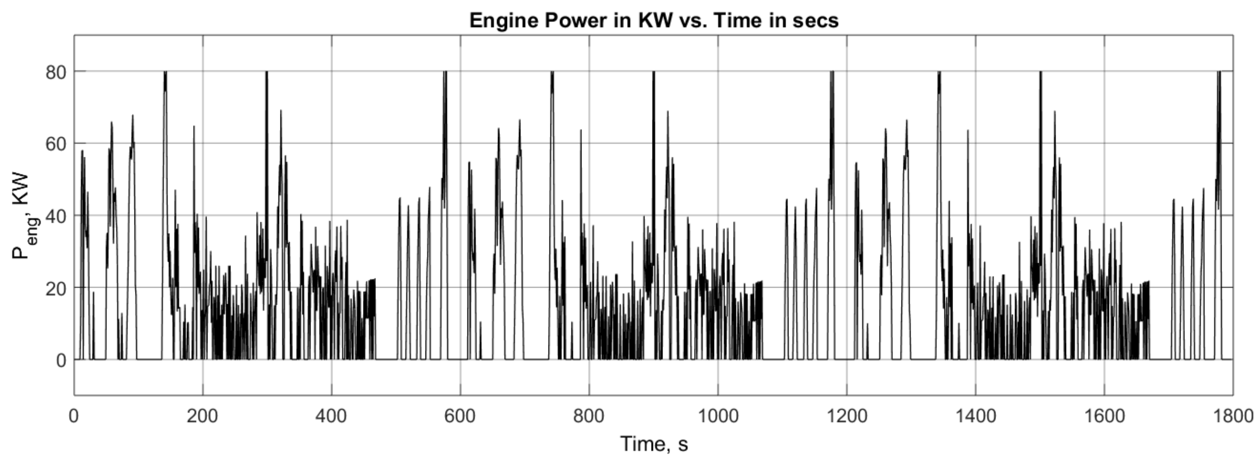

Fig 4: Engine power for US06 cycle. Max power is 80 KW but average power needed is around 20 KW. Max engine power is not needed during max acceleration (~50s). Max power is needed when accelerating in high speed (~300s). Max power is also needed when going to relatively high velocity from zero (~135s and 570s)

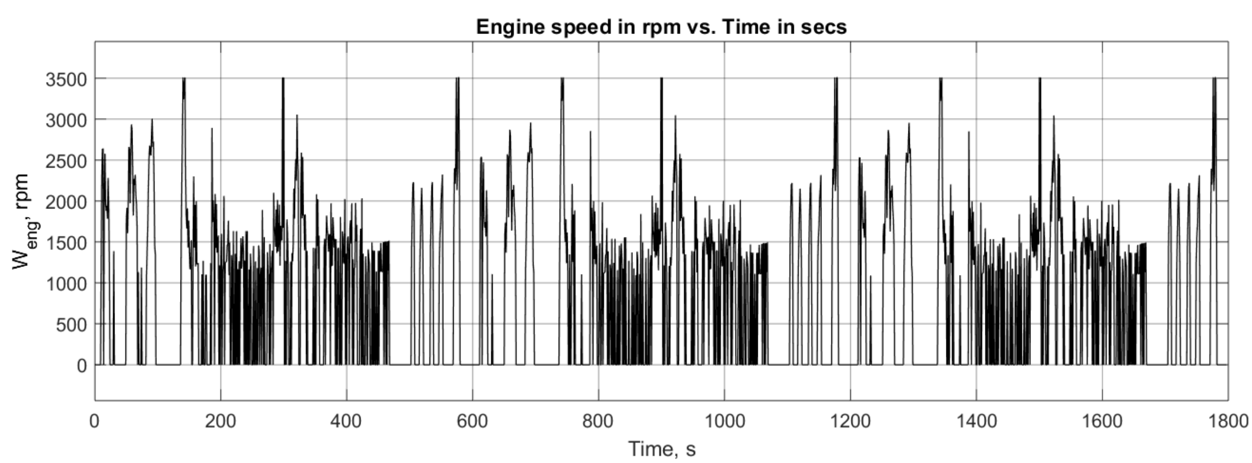

Fig 5: Engine speed for US06 cycle. Max speed is 3500 rpm which is well below normal engine red rpm zone (~5000 rpm). Max rpm needed when rapid acceleration at high speed is needed (~300s). Also, max rpm reached when need to reach high speed rapidly from zero, same as engine power.

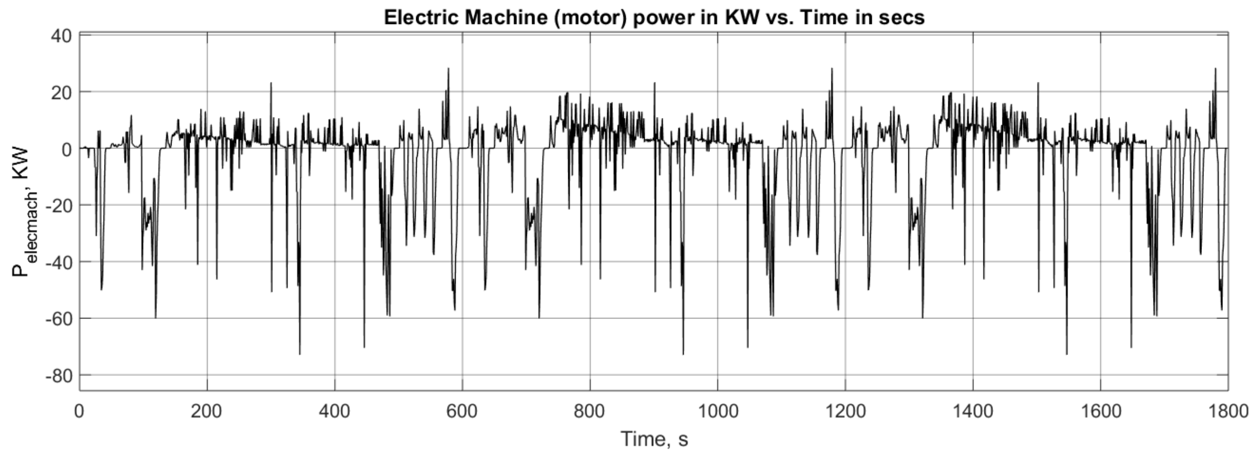

Fig 6: Motor power for US06 cycle. Any power over 80KW or below 10KW is provided solely by motor. Peak power needed when needs acceleration at higher speed. Around 330s of the cycle the vehicle accelerates from a very high speed (70 mph) to higher speed (80mph) which triggers max power. Negative power generated during deceleration, when regenerative braking mode activates. Motor acts as a generator and charges the battery.

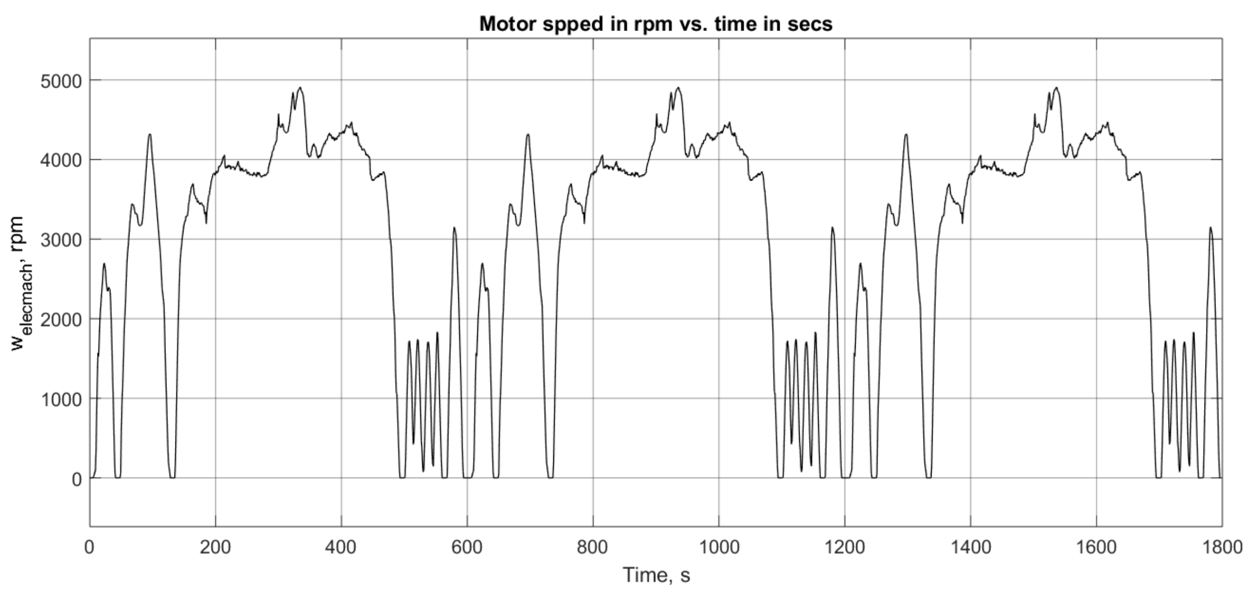

Fig 7: Motor speed in rpm for US06 cycle. Max rpm (~5000 rpm) occurs at the time of max velocity. Motor rpm is calculated from vehicle velocity. As a result this graph looks same as vehicle velocity and max rpm needed at max velocity.

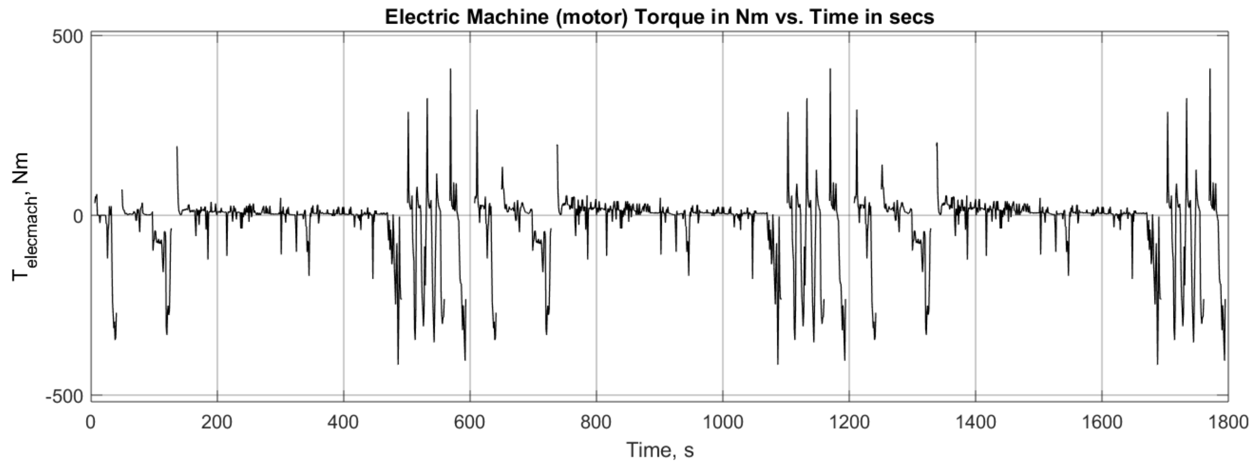

Fig 8: Motor torque in Nm for US06 cycle. Max (positive) torque needed at the time of max acceleration. Min torque needed at the time of max deceleration. Max torque needed at max motor power.

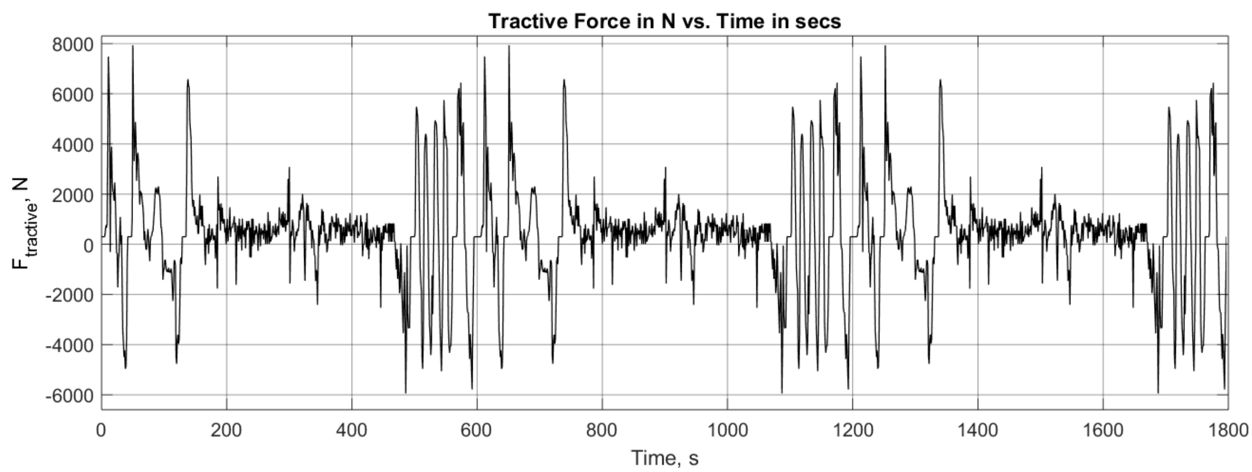

Fig 9: Tractive force in N for US06 cycle. Tractive force depends on velocity and acceleration. As a result, max tractive force occurs at the combination of max velocity and acceleration. Not really needed at high speed acceleration.

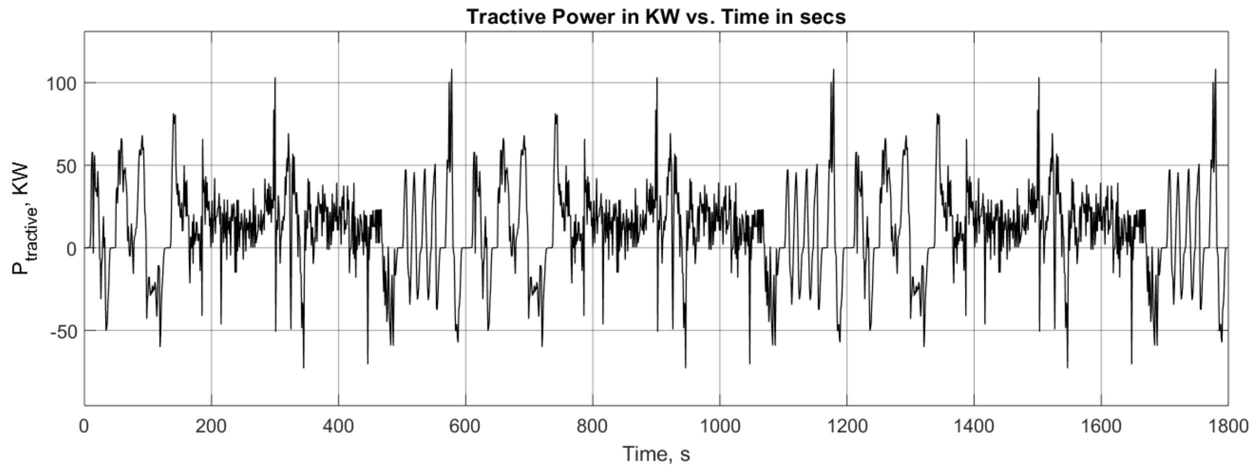

Fig 9: Tractive power in KW for US06 cycle. Max tractive power needed at the time of acceleration at high speed (300s) and at the time of high acceleration and velocity from zero speed (578s). Basically at the time of high torque and rpm.

Table 3: Mpg, SOC and total fuel use for US06 cycle. (default setting in energy management system)

	After 3 cycles
MPG	34.2
SOC	0.658
Fuel	0.23 gal/cycle

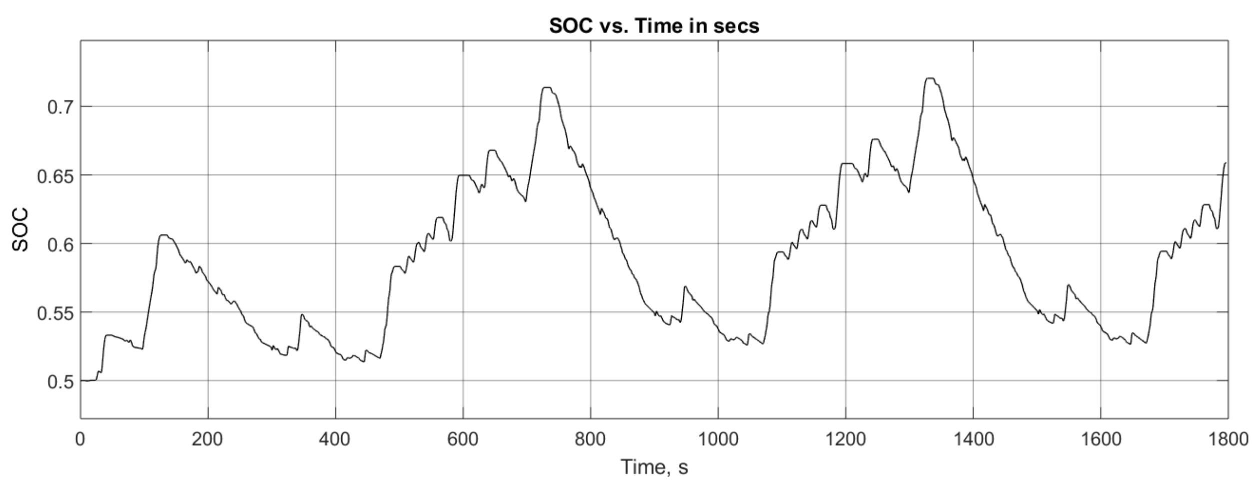

Fig 10: SOC for US06. Ran for several cycle to achieve SS. SOC over 0.5 for all the time. Which shows aggressive ways can be implemented in power management because battery lower safe limit is 0.2.

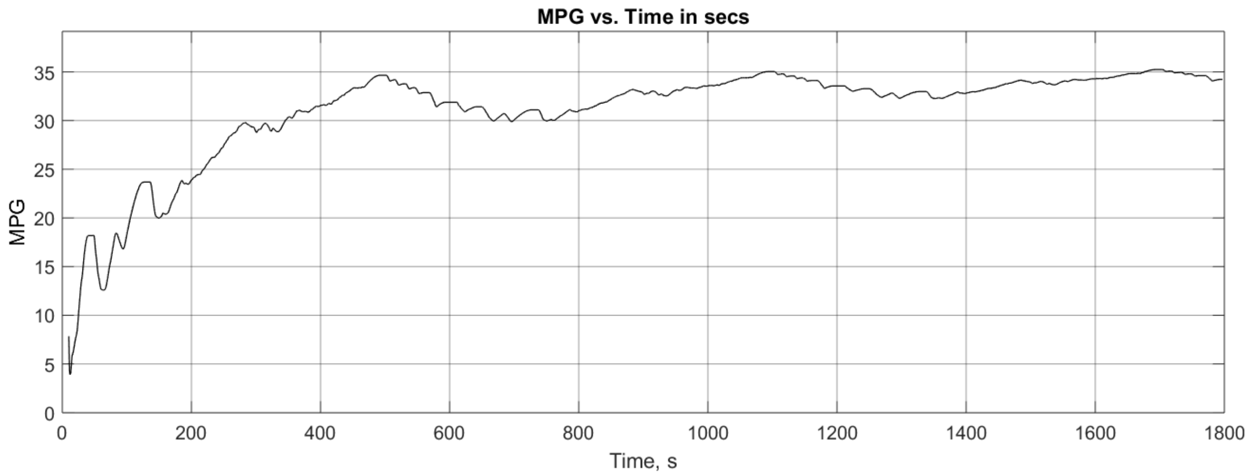

Fig 11: MPG for US06. Ran for several cycle to achieve SS. MPG stays around 35.

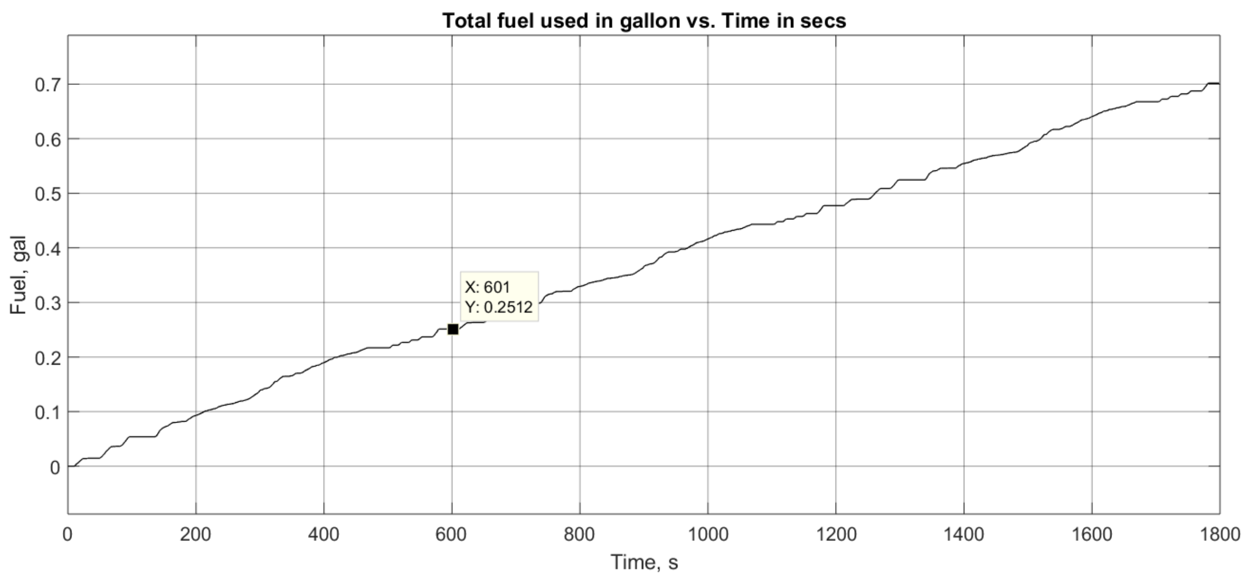

Fig 12: Total fuel for US06. Ran for several cycle to achieve SS. US06 is about 8 miles cycle. So after 3 cycles, 0.7 gallon of fuel needed to cover 24 miles.

Results for cycle LA92

Duration: 1435 seconds

Total distance: 9.8 miles (15.8 km)

Average Speed: 24.8 mi/h (39.6 km/h)

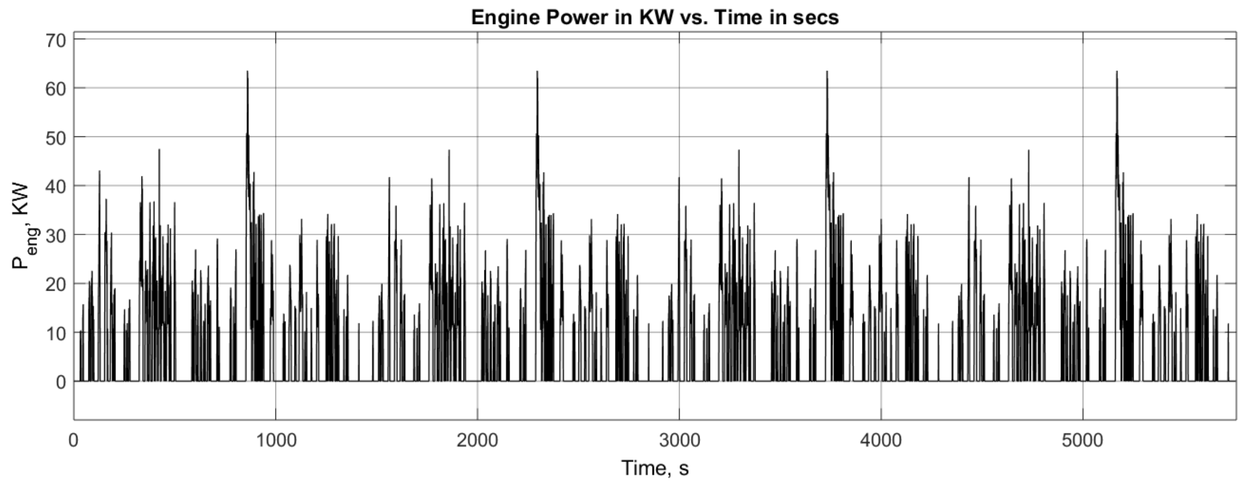

Fig 13: Engine power for LA92 cycle. Max power is 64 KW which is lower than max power limit of 80 KW. So, motor power at high power acceleration stage is not needed. Also, lower size engine can be used here (around 50-55 KW) and extra power can be supplied by battery, which will be more fuel efficient.

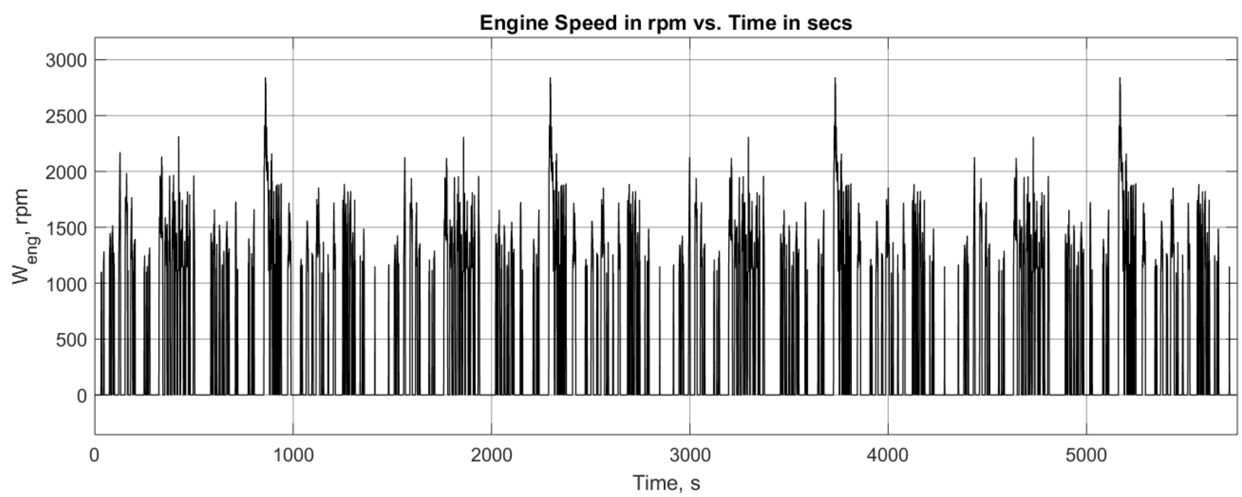

Fig 14: Engine speed for LA92 cycle. Max speed is ~2800 rpm occurs at max power.

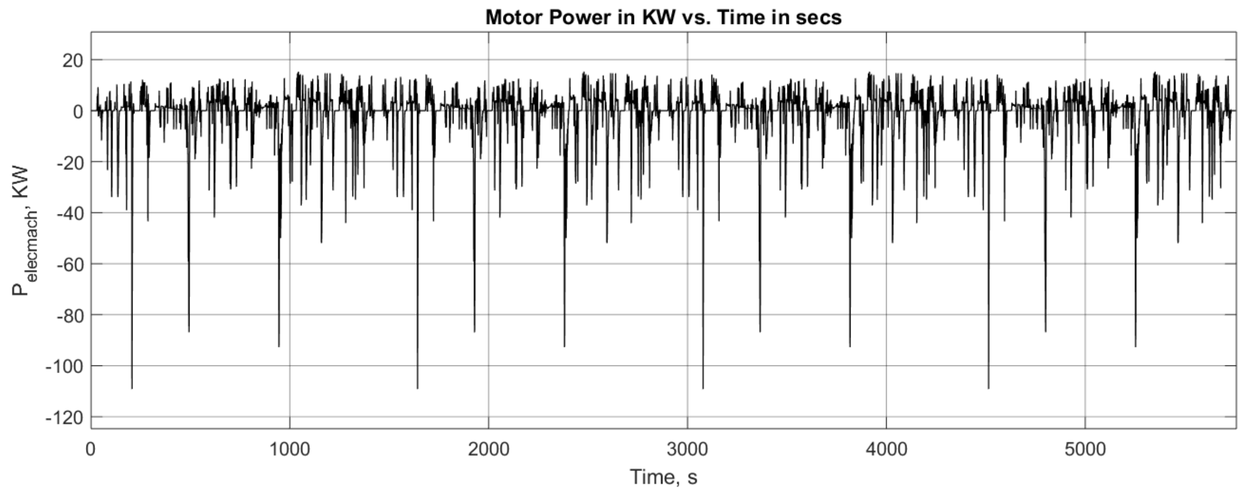

Fig 15: Motor power for LA92 cycle. Any power over 80KW or below 10KW is provided solely by motor. Peak power is not needed when needs acceleration at higher speed. Lots of braking generating a lot of regenerative energy to charge the battery. Also it indicates that, aggressive power management (increasing Pmin to 20 or 30 KW) has better chance of SOC staying within limit.

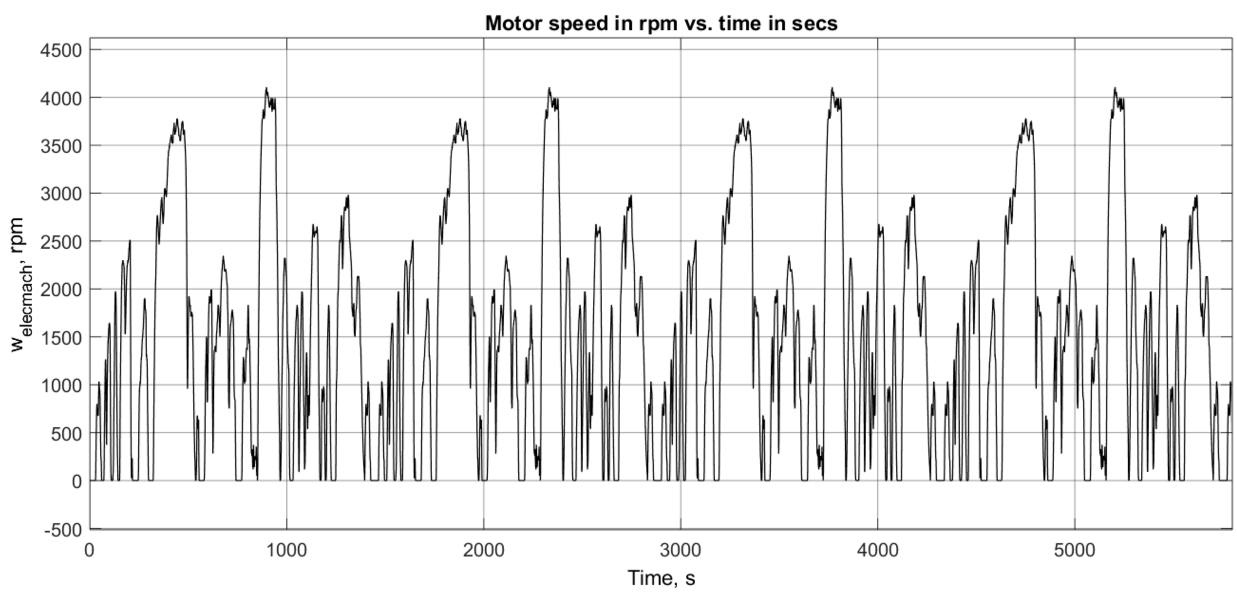

Fig 16: Motor speed in rpm for LA92 cycle. Max rpm (~4050 rpm) occurs at the time of max velocity.

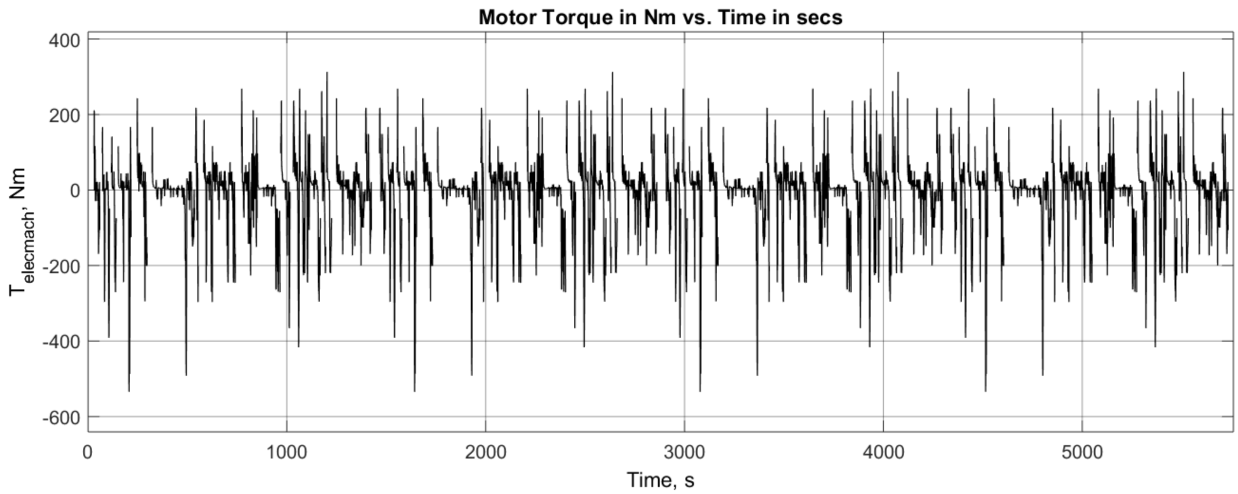

Fig 17: Motor torque in Nm for LA92 cycle. Max (positive) torque needed (1200s) when tractive force is max. This occurs not at max velocity or max acceleration. But at a point when both velocity (from zero) and acceleration is relatively high.

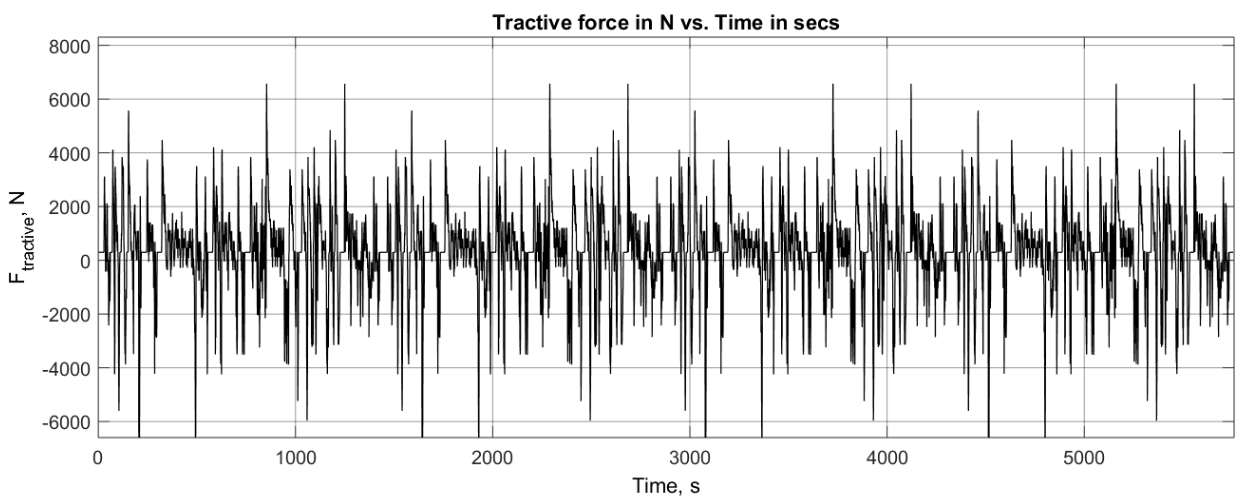

Fig 18: Tractive force in N for LA92 cycle. Tractive force depends on velocity and acceleration. As a result, max tractive force occurs at the combination of max velocity and acceleration.

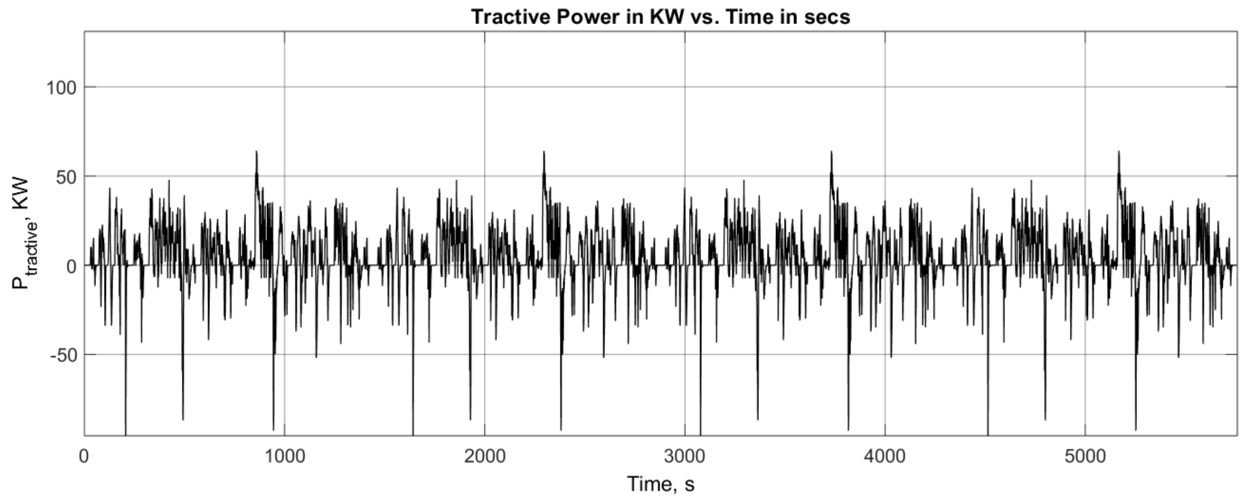

Fig 19: Tractive power in KW for LA92 cycle. As a function of velocity and tractive force (acceleration), it occurs when combination of them is highest. Max positive tractive power is about 64 KW, which indicates lower engine size will be a good idea for this case.

Table 4: Mpg, SOC and total fuel use for LA92 cycle. (default setting in energy management system)

	After 4 cycles
MPG	34.94
SOC	0.55
Fuel	0.3075 gal/cycle

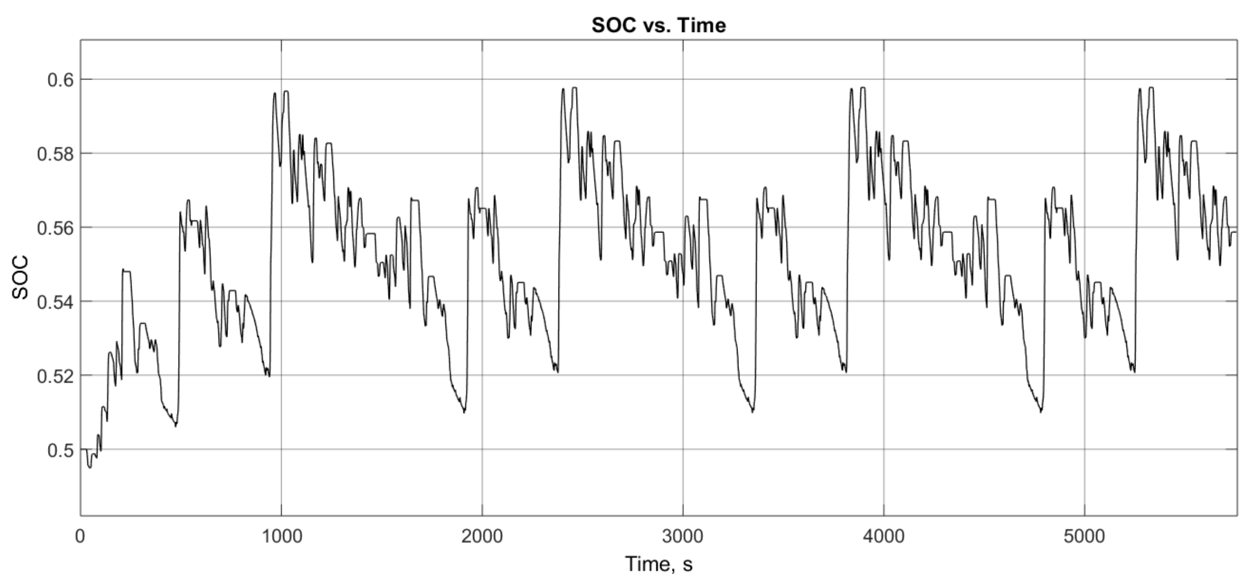

Fig 20: SOC for LA92. Ran for several cycle to achieve SS.

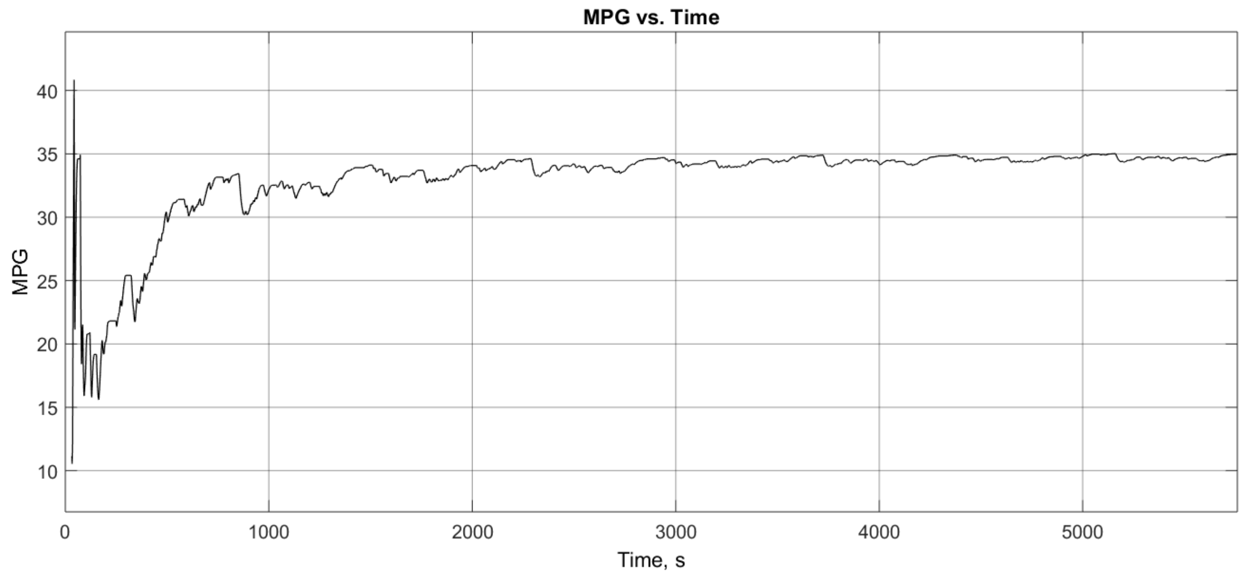

Fig 21: MPG for LA92. Ran for several cycle to achieve SS.

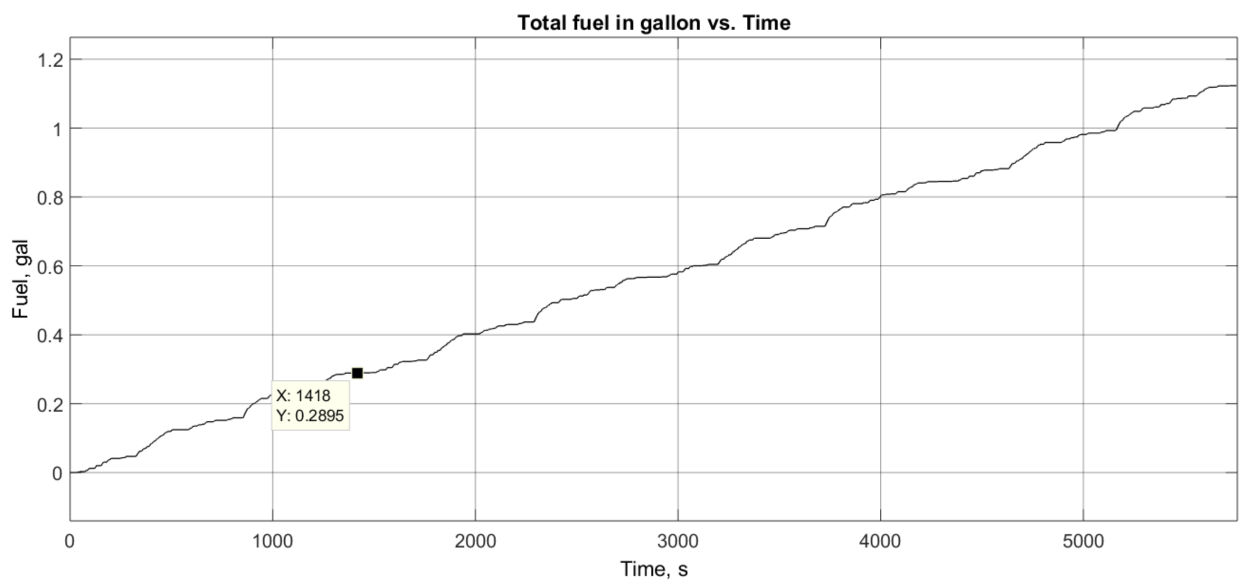

Fig 22: Total fuel for LA92. Ran for several cycle to achieve SS.

Improvements of power management system

1) Minimum bsfc (255 g/kWh) occurs when engine is operating around 3000 rpm and between 55 to 75 KW. But engine minimum power is set 10 KW. Between 10 KW to 60 KW engine is operating is less than optimum way. Increasing the minimum cutoff power of the engine may increase the mpg. But have to look at SOC so that battery can maintain the SOC limit and doesn't discharge very much.

US06

For, E_max = 1.7*1000*3600; %J battery size

Table 5: MPG and SOC for multiple engine Pmin values for US06 cycle and E_max = 1.7*1000*3600.

For, Engine Pmin	mpg	SOC (after 5 cycles)
20 KW	37 (increase)	0.53 (decrease- within limit)
30 KW	47 (increase – a lot)	0.13 (decrease- below 0.2)

Need to increase battery size for sustaining use. Doubling battery size.

For, E_max = 3.4*1000*3600; %J battery size

Table 6: MPG and SOC for multiple engine Pmin values for US06 cycle and E_max = 3.4*1000*3600.

For, Engine Pmin	mpg	SOC (after 5 cycles)
20 KW	37 (same)	0.53 (decrease- within limit)
30 KW	45 (same as last)	0.1 (decrease- below 0.2)

Increasing battery size also increasing battery weight. This seems to affect the SOC not the way we wanted.

LA92

For, E_max = 1.7*1000*3600; %J battery size

Table 7: MPG and SOC for multiple engine Pmin values for LA92 cycle and E_max = 1.7*1000*3600.

For, Engine Pmin	mpg	SOC (after 5 cycles)
20 KW	40 (increase)	0.35 (decrease - over 0.2 all-time)
30 KW	78 (increase – a lot)	Always below 0.1

Need to increase battery size for sustaining use. Doubling battery size.

For, E_max = 3.4*1000*3600; %J battery size

Table 8: MPG and SOC for multiple engine Pmin values for LA92 cycle and E_max = 3.4*1000*3600.

For, Engine Pmin	Mpg	SOC(after 5 cycles)
20 KW	41 (same)	0.34 (same – over 0.2 all-time and lowest point is higher than Emax=1.7 kWh cycle)

30 KW	78 (same as last)	0.0 (decrease- dead)

Increasing battery size also increasing battery weight. This seems not affecting the SOC for LA92 compared to US06.

US06 is highway cycle and LA92 is city cycle. As it seems, city cycle has higher increase in mpg with increasing Pmin.

2) Target SOC is 0.5. If final SOC is over 0.5, then maybe using a smaller battery is fine. Smaller battery has lower weight and that may increase the mpg. Keeping engine Pmin = 10 KW.

US06

Table 9: MPG and SOC for fixed engine Pmin values for US06 cycle and multiple E_max.

Battery size	mpg	SOC (after 4 cycles)
E_max = 1*1000*3600; %J battery size	35	0.65
E_max = 1.7*1000*3600; %J battery size	34.9	0.66
E_max = 3.4*1000*3600; %J battery size	34	0.62

LA92

Table 10: MPG and SOC for fixed engine Pmin values for LA92 cycle and multiple E_max.

Battery size	mpg	SOC (after 4 cycles)
E_max = 1*1000*3600; %J battery size	35	0.575
E_max = 1.7*1000*3600; %J battery size	35	0.57
E_max = 3.4*1000*3600; %J battery size	33	0.565

Changing battery size only doesn't seem to affect mpg that much for both cycles. With increasing battery, mpg decreasing slightly due to higher weight.

3) For charge sustaining mode: P_elecmach = -(P_max - P_tractive)*(0.5-SOC)

Which means, if SOC goes below threshold = 0.5 engine power recharges. We can use a threshold lower than 0.5. This may decrease battery life but should increase mpg, because more battery power is used cumulatively. Pmin = 10KW, E_max = 1.7*1000*3600.

US06

Table 11: MPG and SOC for multiple threshold values for US06 cycle.

Threshold	mpg	SOC (after 5 cycles)
0.5	34	0.65
0.4	35	0.52
0.3	36	0.42 (below 0.2)
0.2	36.2	0.32 (below 0.2)

LA92

Table 12: MPG and SOC for multiple threshold values for LA92 cycle.

Threshold	mpg	SOC (after 5 cycles)
0.5	35	0.55
0.4	35.5	0.45
0.3	36.2	0.35 (below 0.2)
0.2	37	0.25 (below 0.2)

4) The focus of this exercise is to increase mpg while keeping battery SOC within 0.2 – 0.8.

Another aggressive mode of charging could be following during charge sustaining mode:

P_elecmach = -(P_max-P_tractive)*sign(0.5-SOC)

This provides bigger power from motor as a result SOC should decrease rapidly compared to default mode.

US06

For, E_max = 1.7*1000*3600; %J battery size

Table 13: MPG and SOC for multiple engine Pmin values for US06 cycle and E_max = 1.7*1000*3600.

For, Engine Pmin	mpg	SOC (after 5 cycles)
20 KW	35 (increase)	0.52 (decrease- within limit)
30 KW	37 (increase)	0.37 (decrease- below 0.2 for very short time)

LA92

For, E_max = 1.7*1000*3600; %J battery size

Table 14: MPG and SOC for multiple engine Pmin values for LA92 cycle and E_max = 1.7*1000*3600.

For, Engine Pmin	mpg	SOC (after 5 cycles)
20 KW	38 (increase)	0.5 (decrease- within limit)
30 KW	55 (increase)	0.05 (below 0.2 for all the time)

Higher increase in mpg is observed for city drive cycle (LA92).

5) Decreasing Pmax from 80KW for more aggressive power management will negatively affect US06 cycle battery because total tractive power is over 100KW. But for LA92, we can lower the Pmax value and still expect the SOC to be within limit because Max tractive power is only 64 KW.

US06

For, E_max = 1.7*1000*3600; %J battery size

Table 13: MPG and SOC for multiple engine Pmax values for US06 cycle and E_max = 1.7 KW hr.

For, Engine Pmin	mpg	SOC (after 3 cycles)
70 KW	34 (about same)	0.67 (almost same)
50 KW	33.7 (decrease)	0.7 (increase)
30 KW	33.2 (decrease)	0.48 (decrease)

MPG decreasing because engine is operating at the bsfc sweet spot which between 55-75 KW. So, if we decrease Pmax below 55 KW, that will always negatively impact mpg.

LA92

For, E_max = 1.7*1000*3600; %J battery size

Table 14: MPG and SOC for multiple engine Pmax values for LA92 cycle and E_max = 1.7 KW hr.

For, Engine Pmin	mpg	SOC (after 4 cycles)
70 KW	35 (same)	0.57 (increase)
60 KW	35 (same)	0.59 (increase)
50 KW	35 (same)	0.62 (increase)

SOC depends on motor power. As we decrease engine power, motor power increase. And this increases SOC until engine inefficiency decreases mpg (as seen for US06 cycle). With smaller engine, more aggressive power management can be used to increase mpg.

Conclusions:

1) A Simulink model of the parallel hybrid vehicle was created. All the necessary variables are plotted. All the necessary analysis asked in project 1 is completed.
2) Increasing Engine cutoff power (Pmin) increases mpg. But it also needs higher power from battery (bigger battery). Increasing battery size also increases battery weight which adversely affects mpg. This shows the importance of research on battery capacity to increase hybrid vehicle mpg. Increasing the battery size does not increase mpg and also maintain SOC within the desired limit. This indicates the given battery energy density is too low.
3) Mpg increases more rapidly in urban stop and go cycle (LA92), than moderately highway cycle (US06).
4) Increasing battery size (keeping very other variables same) decreases mpg.
5) Decreasing the threshold to a certain limit in charge sustaining mode increases mpg. After that, battery weight is too high for any improvement.
6) Using more aggressive power management (taking more power from motor) increases mpg more rapidly but decreases SOC more rapidly too.
7) Decreasing Max engine power decreases mpg but increases SOC.
8) Rule based optimization (what we are doing) is easy to implement and also provides insight into the system. But when too many variables are involved, it is hard to keep track of all the variables. A generalized optimization method may show us where the highest optimization (max mpg) happens. Then going to that optimization point through rule-based method could be a good exercise.
9) Engine and motor mass can be considered separately to analyze how that affects when different sizes of engine (based on Pmax and Pmin) and motor is used.