Clemson University CU-ICAR AUE 817 Final Project

Sizing and Controlling of a Parallel Hybrid SUV Powertrain

Team 3:

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1. Introduction

1.1. Objectives:

The objectives in this project are to size the powertrain components and develop a control strategy of a parallel hybrid SUV to achieve the following requirements:

- 2020 CAFE target for Light duty truck of footprint (47.5 sq.ft): 34.6 MPG
- Top speed>100MPH
- 0-60 mph time (with 75 kg driver)<9.0 s
- Overall range in miles =350 miles (based on EPA 2-cycle combined)
- Brake energy recovery; no plug in.

One of the challenges in components sizing is to balance the competing requirements of fuel economy and power. The power demand during most of the driving cycle is not much, so downsize the engine can improve fuel economy. However, downsize the engine will reduce the maximum power and increase 0-60 mph time. The other challenges is changing one component will affect others, so iteration is needed due to the process as shown in figure 1.

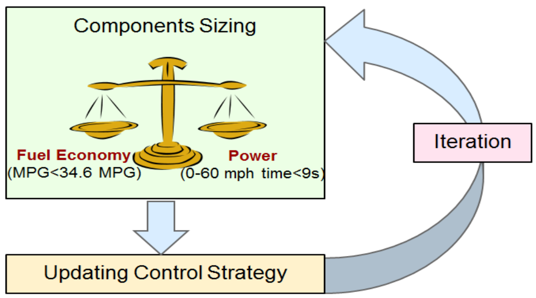


Figure.1 Challenges in the project

1.2. Vehicle configuration:

The vehicle use 4 wheel drive parallel configuration as shown in figure 2. Engine powers front wheels and electric model powers rear wheels. Engine and electric motor are connected by road.

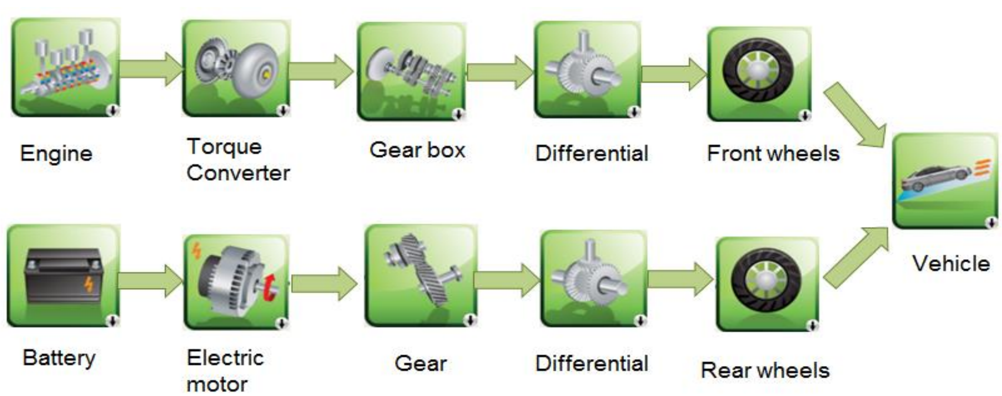


Figure. 2 Vehicle configurations

Some vehicle parameters are listed below:

Table1 Vehicle parameters

Vehicle parameters:	Transmission:
Frontal area A = 2.48 m^2	4 speed Automatic Transmission:
Curb weight = 1300 kg, GVWR = 1750 kg	Gear ratio: 2.847, 1.552, 1.000, 0.700
Rolling resistance coefficient Cr = 0.008	Differential ration: 4.13
Aerodynamic drag coefficient Cd = 0.32	Shift points under normal driving loads
Tire size: 255/55R18, dynamic rolling radius = 357mm	1→2 @1,500 RPM
Rotating inertia: 1.4 kgm2 (per wheel)	2→3 @2,000 RPM
	3→4 @2,500 RPM

2. Powertrain scaling:

2.1. Engine Scaling:

Engine scaling is done by using Willans line model. Firstly, an engine fuel map base on *Torque* (T_e) and *speed* (ω) is converted to a dimensionless map based on Mean Effective Pressure (p_{me}) and Mean piston speed (c_m).

$$P_{me} = \frac{2\pi n_r T_e}{V_d} = \frac{2\pi n_r P}{V_d w} = \frac{2\pi n_r P}{V_d \frac{C_m}{S}\pi} = \frac{2\pi n_r P}{4\frac{\pi B^2}{4} \cdot \frac{C_m}{S}\pi} \quad (1.1)$$

$$P = \frac{\pi P_{me} C_m}{2n_r} \times B^2 \quad (1.2)$$

The relationship of engine power and geometry can be described as.

$$P \propto B^2 \quad (1.3)$$

$$m_{engine} \propto B^2 S \quad (1.4)$$

Willan's Line Model

$$P_{me} = eP_{ma} - P_{ml} \quad (1.5)$$

$$e = (c_1 + c_2 C_m + c_3 C_m^2) - (c_4 + c_5 C_m) P_{ma} \quad (1.6)$$

$$P_{ml} = c_6 + c_7 C_m^2 \quad (1.7)$$

Based on the given T, $\dot{m}$ and w, three parameters (Cm, Pme and Pma) can be calculated at each operation points as follows,

$$C_m = \frac{S}{\pi} w \quad (1.8)$$

$$P_{me} = \frac{2\pi n_r T}{V_d} \quad (1.9)$$

$$P_{ma} = \frac{2\pi n_r}{V_d} \frac{\dot{m} Q_{LHV}}{w} \quad (1.10)$$

According to

$$Ac = B \rightarrow c = A^{-1}B \quad (1.11)$$

$$c = [c_1\ c_2\ c_3\ c_4\ c_5\ c_6\ c_7]^T \quad (1.12)$$

In order to ensure $det(A^T A) \neq 0$, A[7× 7] and B[7× 1] is designed as follows,

$$A(1,:) = [P_{ma} \quad C_m P_{ma} \quad C_m^2 P_{ma} \quad -P_{ma}^2 \quad -C_m P_{ma}^2 \quad -1 \quad -C_m^2\ ] \quad (1.13)$$

$$B(1,1) = P_{me} \quad (1.14)$$

For the A(2,:) to A(7,:) and B(2,1) to B(7,1), based on A(1,:) and B(1,1), each component is multiplied by C_m, C_m^2, C_m^3, P_{ma}, P_{ma}^2 and P_{ma}^3, which is used to avoid singular problem. For each engine operating point, we can get an A and a B. Then by sweeping engine speed and engine torque, we can get a series of A and B. At the same time, we add A together. Then by using $c = A^{-1}B$ we can get the coefficient of Willans Line Model.

c=[0.6017 0.0078 -0.0013 9.87e-8 -5.1e-9 2.88e5 -1.9e-14]^T

For the new engine, we set the engine speed range (750~6300RPM), and raw torque range (0~200Nm). Based on the new engine bore and cylinder diameter, dimensionless parameters (Cm and Pme) are calculated. With the Willans line model coefficient, e and Pml are presented by Cm and Pma. Then the Pma of the new engine is solved in the following equation:

$$P_{me} = [a - bP_{ma}]P_{ma} - P_{ml} \quad (1.15)$$

$$b = (c_1 + c_2 C_m + c_3 C_m^2) \quad (1.16)$$

$$a = (c_4 + c_5 C_m) \quad (1.17)$$

We can get Pma of the new engine:

$$P_{ma} = \frac{b - \sqrt{b^2 - 4a(P_{me} + P_{ml})}}{2a} \quad (1.18)$$

If $b^2 - 4a(P_{me} + P_{ml}) < 0$, there is no solution for above equation. NaN is allocated to P_{ma}.
Then we calculated the fuel conversion efficiency and mass consumption:

$$\eta = \frac{P_{me}}{P_{ma}} \quad (1.19), \qquad \dot{m} = \frac{P_{ma} V_d w}{2\pi n_r Q_{LHV}} \quad (1.20)$$

The efficiency map is given. The red circle refers to the maximum torque @4400RPM, which is the demand of the standard engine in the final project introduction. We can see that it locates right at the peak point over the whole maximum torque output line. So the scaling meets the requirement.

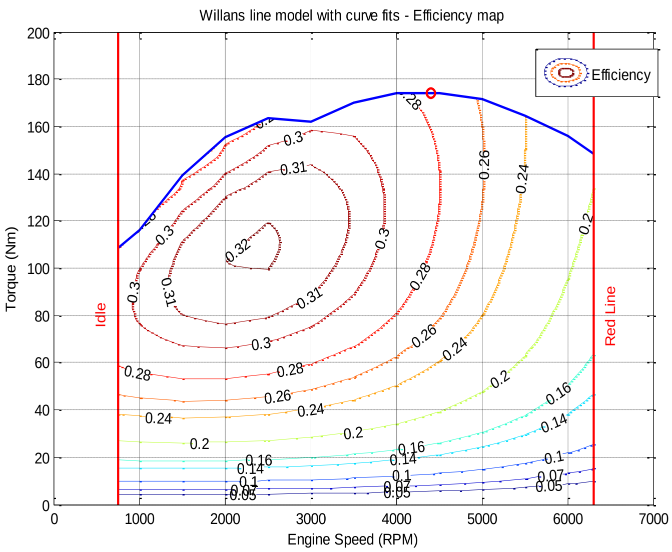


Figure. 3 Willan's line model with curve fits.

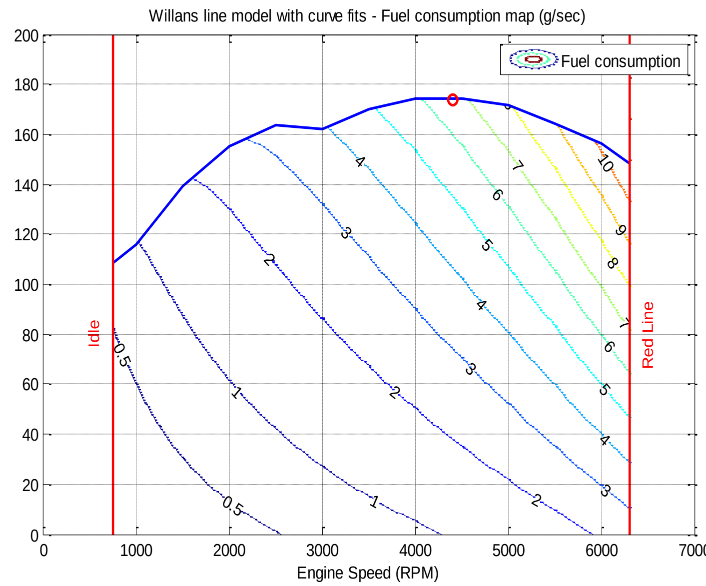


Figure. 4 Fuel consumption map.

The following is the maximum power line over the engine speed. The peak power output is 98kW @6300 RPM (red circle in the figure), which meets the requirement of the standard engine.

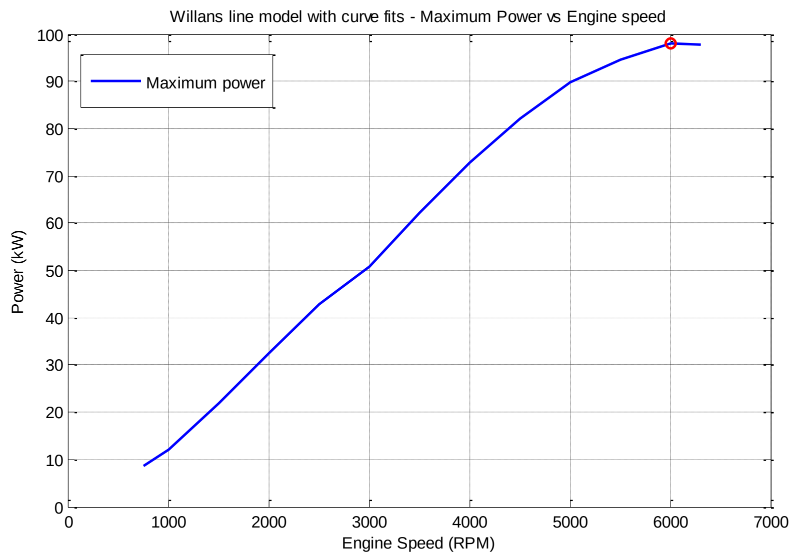


Figure.5 Maximum power vs engine speed

Based on the standard engine, we scale it and get our new engine to optimize the fuel economy of the whole hybrid vehicle. Finally, the 1.3 liters engine is used to power our hybrid vehicle. The map is give as follows.

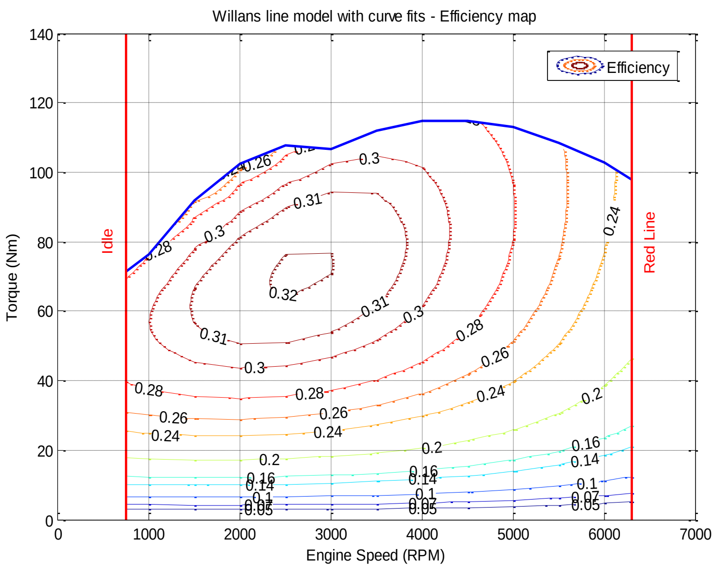


Figure. 6 1.3 liters engine efficiency map

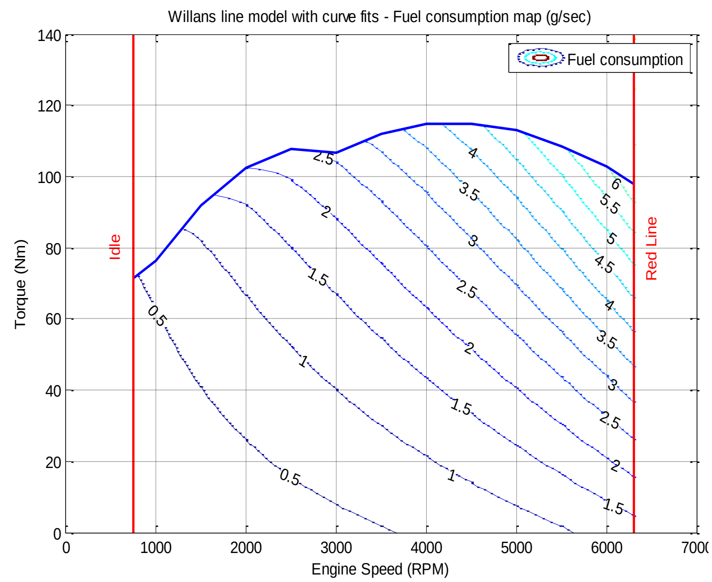


Figure. 7 1.3 liters engine and fuel map

New engine specifications:

Mass	130kg
Displacement	1.3L
Bore	72.1mm
Stroke	79.4mm
Peak torque	115Nm @4400RPM
Peak power	65kW @ 6000RPM

2.2. Electric Motor scaling

The process of electric motor scaling is similar to the engine scaling. Firstly, the data of a known electric motor is converted to scale independent of machine geometry. Secondly, the dimensionless the dimensionless model is fitted to Willans line model. Finally, machines characteristics of different size are obtained by converting the dimensionless model back to dimensional model.

2.2.1. Convert torque and speed into mean effective pressure.

The dimensionless Willans line model is based on Mean Effective Pressure *(p_{me})* and Mean piston speed (c_m). Their relationships with *Torque (T_e)* and *speed* (ω) are described in the flowering equations:

$$c_m = r\omega \ (2.1); \qquad p_{me} = \frac{T_e}{2\pi r^2 l} \ (2.2)$$

$$P = T_e\omega = \ 2\pi \, r \, l \, c_m \, p_{me} \ (2.3)$$

We assume the motor's the same radius to length ratio across machines of different size. Therefore, motor's power is proportional to the square of motor's length.

$$P \propto \ l^2 \ (2.4)$$

We have known the geometry of a 105 kW motor and the efficiency map of a 84 kW motor. The geometry of the 84 kW motor can be derived from the following equations:

$$l_1 = l_2\sqrt{\frac{P_1}{P_2}} = 300 * \sqrt{\frac{84}{120}} = 251\ mm; \quad r_1 = r_2\sqrt{\frac{P_1}{P_2}} = \frac{1}{2} * 225 * \sqrt{\frac{84}{120}} = 101\ mm$$

The convert the efficiency map based on p_{me} and c_m is shown in the figure below:

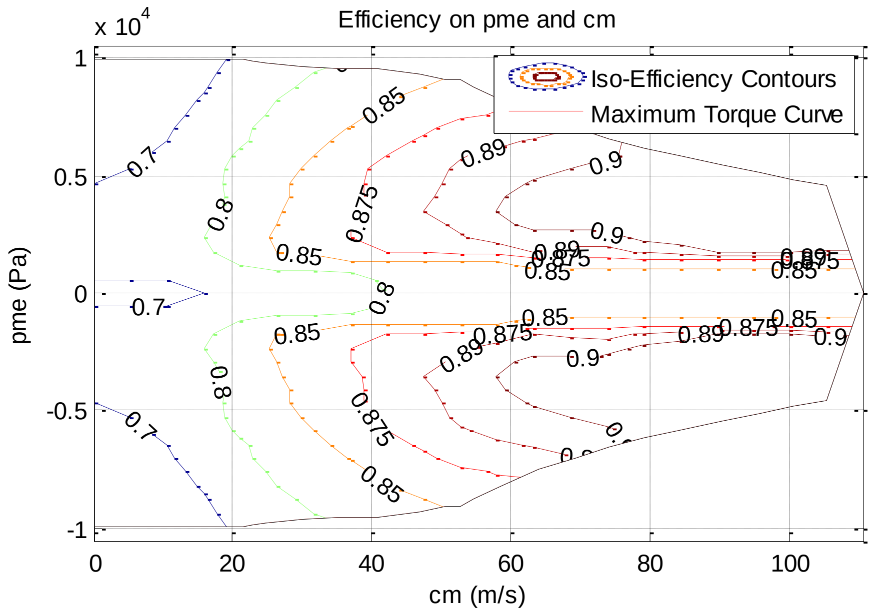


Figure.7 84 kw engine efficiency map on pme and cm

2.2.2. Curve fitting:

Motor's efficiency (η) can be described from the equation below, where p_{ma} is the mechanical power, p_{me} is the electrical power:

$$\eta_{ch} = \frac{p_{me}}{p_{ma}}\ (dis\text{changing})\ (2.5)$$

$$\eta_{disch} = \frac{p_{me}}{p_{ma}}\ (\text{changing})\ (2.6)$$

$$p_{ma} = T_e\omega\ \ (2.7)$$

$$p_{me} = e\ p_{ma} - p_{loss}\ \ (2.8)$$

The slope e and intercept p_{loss} can be parameterized with polynomial functions of *cm*

$$e = \sum_{i=0}^{n} \alpha_{ei} c_m^i\ \ (2.9)$$

$$p_{loss} = \sum_{i=0}^{n} \beta_{li} c_m^i \quad (2.10)$$

We chose second order polynomial functions:

$$e = \alpha_0 + \alpha_1 c_m + \alpha_2 c_m^2 \quad (2.11)$$

$$p_{loss} = \beta_0 + \beta_1 c_m + \beta_2 c_m^2 \quad (2.12)$$

$$p_{me} = (\alpha_0 + \alpha_1 c_m + \alpha_2 c_m^2)\, p_{ma} - (\beta_0 + \beta_1 c_m + \beta_2 c_m^2) \quad (2.13)$$

Least square method is used in data fitting, the result in shown in the table below:

a0	0.554	b0	-606
a1	0.00806	b1	13.3
a2	-4.84E-05	b2	-0.0822

Goodness of fit: R-square: 0.996.

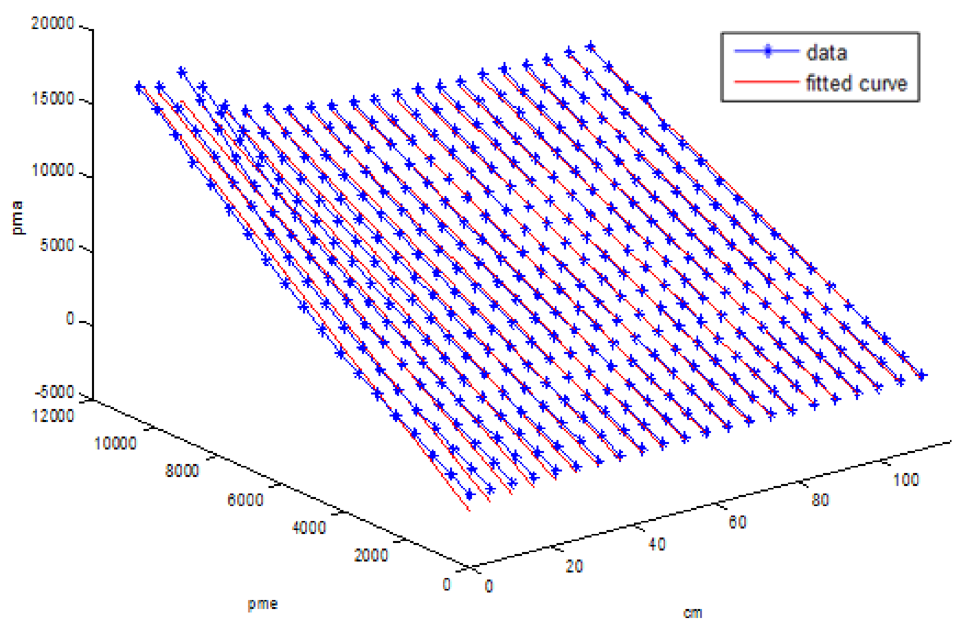


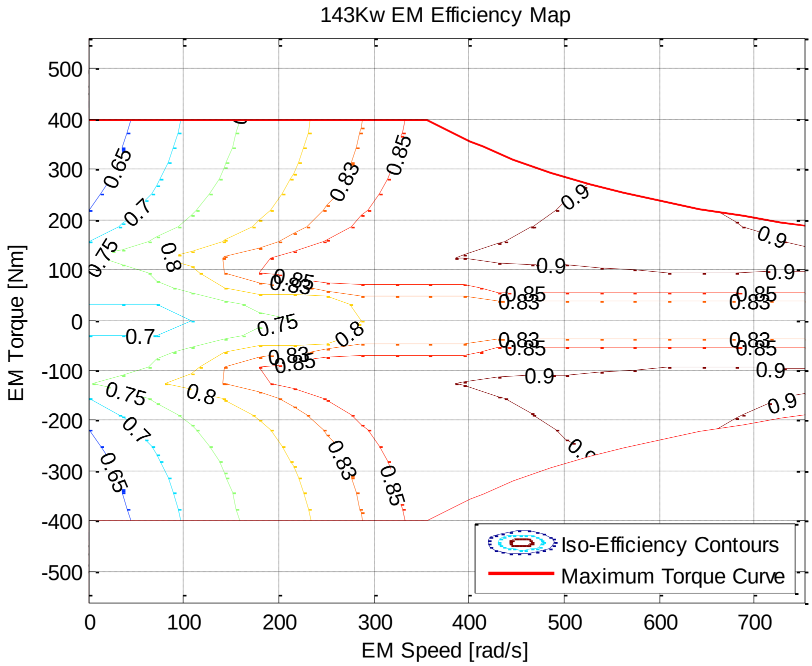
Figure.8 Willans line model curve fitting original data vs fitted curve .

The dot line is the actual data and the solid line the fitting data. In general, fitting the data very well

2.2.3. Size the machine based on scalable Willan's line model

After we obtained the dimensionless model, the efficiency map of the new machine can be obtained by simplify convert the map back to the basis of *Torque* (T_e) and *speed* (ω) using equations 2.1 to 2.3.

We chose a motor of higher power the specifications and efficiency map of the motor is shown in the table and figure below.



Motor specifications	
Max Power	143 Kw
Max Torque	400 Nm (0-357 rad/s)
Radius	57.6 mm
Length	392 mm

Figure.9 The efficiency map of the 143 kW motor

2.3. Battery Modeling

2.3.1. Battery model fitting steps:

Step 1: Pick and digitize points on the given discharging and charging curves.

A free software Plot digitizer is used in this step. For example, the following picture is showing how to pick points on the discharging curve (item=1C). Repeat the process for the rest four curves and charging curve, save the data in Matlab Workspace, and they are good to use.

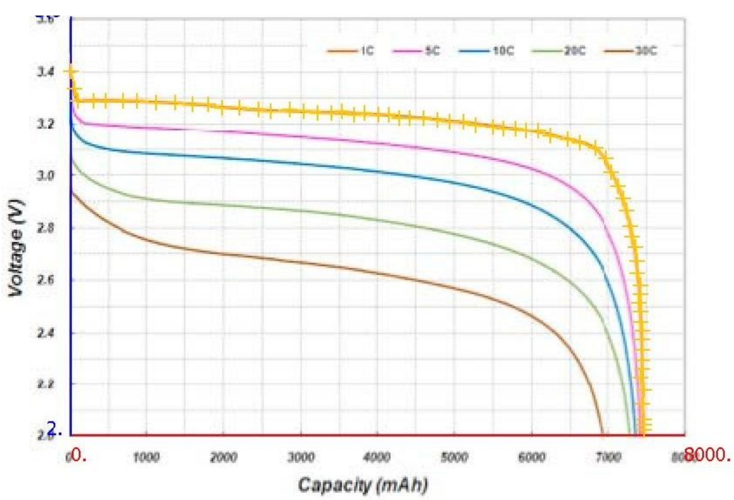


Figure.10 battery dataset

Step 2: Find peukert equation parameters ‘k’ and ‘n’.

To find the peukert equation number, 5 original data pairs (C_I, I) , corresponding to voltage =2.0V, are needed. With the data pairs, nonlinear fit is implemented and parameters 'k' and 'n' are obtained,

$$C_I = 7521 * I^{-0.01692} \quad (3.1)$$

Then the equation is used for normalizing SOC, which can be expressed by the following equation:

$$\mathrm{SOC} = \frac{C_I - Discharge\ Cap}{C_I} * 100\% \quad (3.2)$$

Step 2：Identify the parameters of f (V) using the method provided in Lecture 14&15 Appendix. And least square fitting is implemented here.

Take discharging as an example, data from 1C, 5C, 20C, 30C are used to identify to coefficients, and data of 10C are going to be used for validation, which will be talked about later. The process can be better explained by the following code:

```
C=zeros(length(T),12);
A=zeros(length(T),12);

for i=1:length(T)
    C(i,:)=[1 SOC(i) SOC(i)^2 T(i) SOC(i)*T(i) SOC(i)^2*T(i) -I(i) -
I(i)*SOC(i) -I(i)*SOC(i)^2 -I(i)*T(i) -I(i)*SOC(i)*T(i) -I(i)*SOC(i)^2*T(i)];
    A(i,:)=[0 0 0 0 0 0 -1 -SOC(i) -SOC(i)^2 -T(i) -SOC(i)*T(i) -
SOC(i)^2*T(i)]; % the Coefficient matrix of resistance
end
d=V';
b=-0.001*ones(length(T),1);
X = lsqlin(C,d,A,b);
```

Then the 12 coefficients are acquired

$\alpha_0 = 12.01$	$\alpha_1 = -5.74$	$\alpha_2 = 3.92$	$\alpha_3 = -0.03$	$\alpha_4 = 0.02$	$\alpha_5 = -0.01$
$\beta_0 = 0.19$	$\beta_1 = -0.48$	$\beta_2 = 0.36$	$\beta_3 = 5e - 4$	$\beta_3 = 0.001$	$\beta_3 = -0.001$

When dealing with charging, it is basically the same process and unnecessary to go into details. And the coefficients for charging are:

$\alpha_0 = 3.39$	$\alpha_1 = 0.07$	$\alpha_2 = -0.22$	$\alpha_3 = 0$	$\alpha_4 = 0$	$\alpha_5 = 0$
$\beta_0 = e - 3$	$\beta_1 - 7.32$	$\beta_2 = 6.67$	$\beta_3 = 0$	$\beta_3 = 0$	$\beta_3 = 0$

Step 3: Coefficients validation.

Data of 10C curve for discharging and 2C for charging are not used to identify parameters in step 2, so they are now used to validate the coefficient obtained. The results are shown as below:

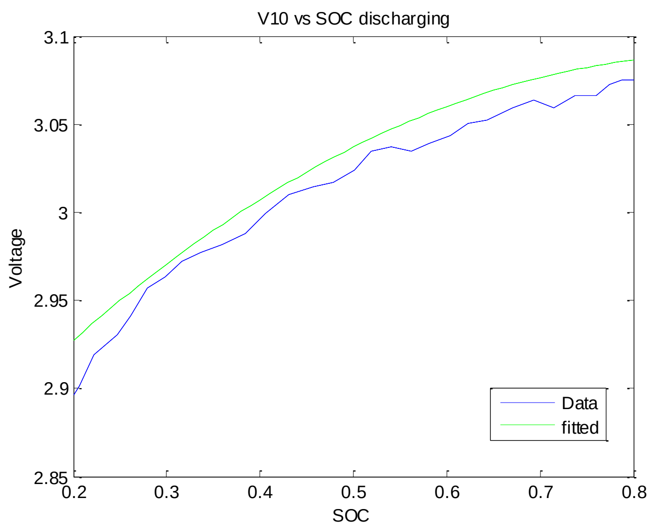


Figure.10 comparison between original data and fitted curve V10 vs SOC discharging

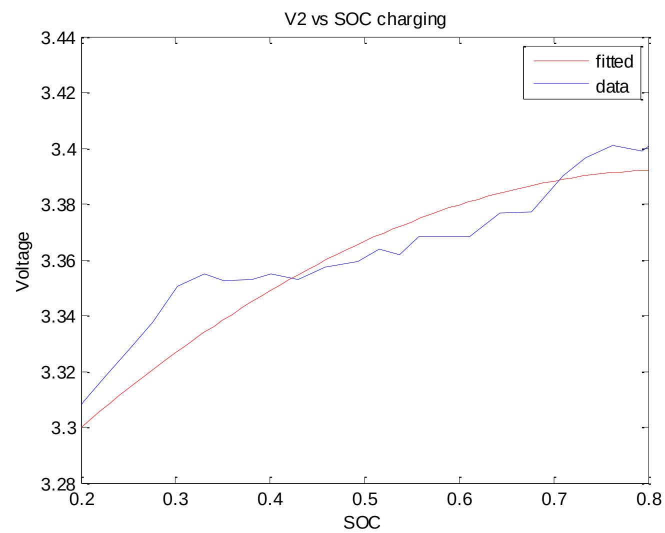


Figure.11 comparison between original data and fitted curve V2 vs SOC charging

As we can see, the fitting results are acceptable, though not perfect.

Step 4: Plot E_0 and R.

We can see by now we have built the model of E_0 and R successfully. And here are the plots of E0 and R for both charging and discharging.

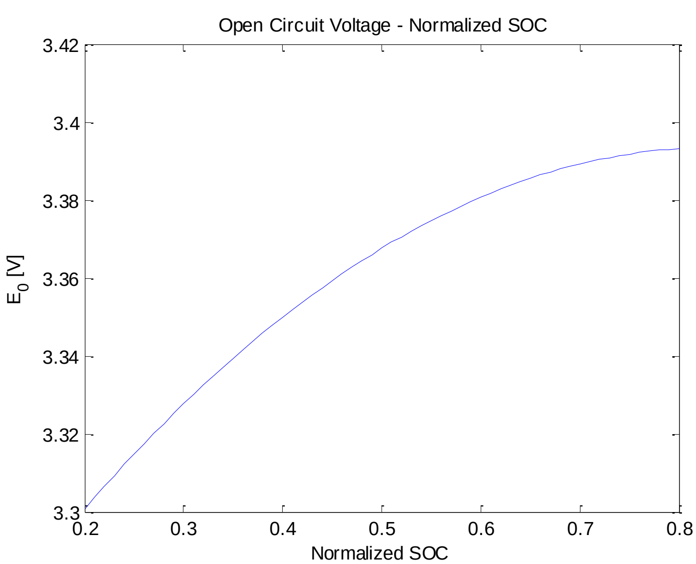


Figure. 12 open circuit voltage vs SOC charge

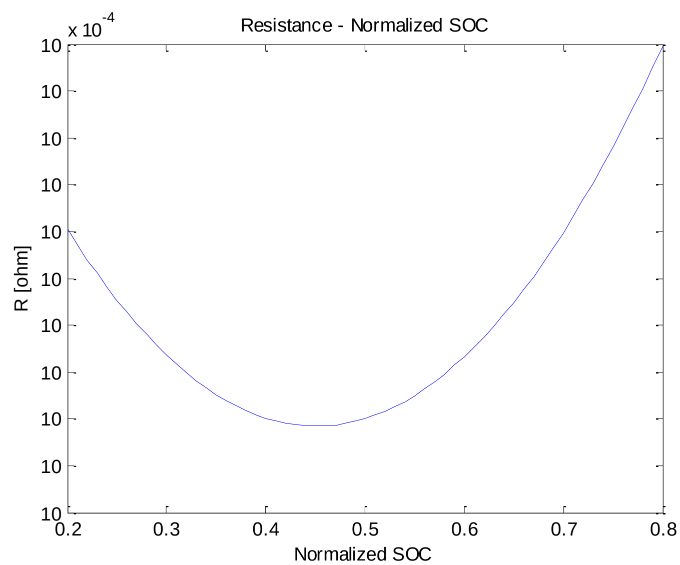


Figure. 13 Resistance vs SOC charge

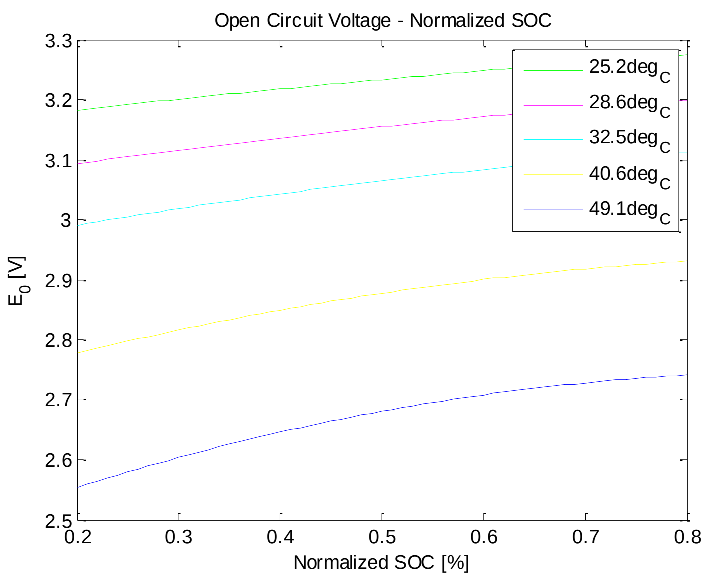


Figure. 14 open circuit voltage vs SOC discharge

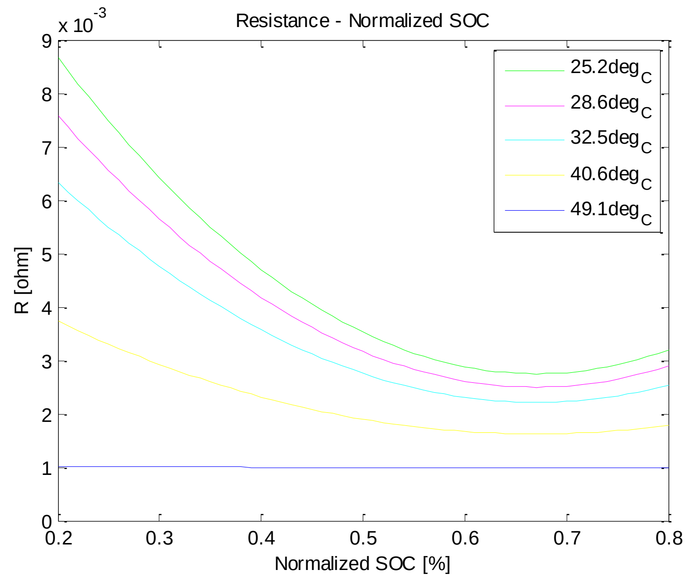


Figure. 15 Resistance vs SOC discharge

We obtain one single curve in charging plots because the charging process is independent from temperature. We do obtain multiple curves for different temperatures in discharging curves though.

One thing worth mention here is that due to restriction of positive R added when fitting, we note that R curve in charging and R curve of 49.1deg_C in discharging have minimal variations. And the variations do exist as SOC changes.

2.3.2. Battery pack and fuel tank sizing

First of all, number of battery cells has to be determined. In our case, it is determined mainly by max power required by the motor. Max power output for a single cell is 0.758kW. With an 186kW motor, 247 cells are needed in our vehicle. The result shows that the volume of our battery pack has 144 cells and its mass is 105kg.And with a cruise range of 350 miles, an 8.5 gallon fuel tank is needed.

2.3.3. Simulink Model of the battery pack.

The picture below is the Simulink model of our battery pack. We have three inputs, SOC, T, current, since the open circuit voltage is the function of these three values. Then we need to choose which map we are going to use, which is determined by whether the motor power is greater than zero or smaller than zero, namely, the battery is discharging or charging. That's how our battery model just built is implemented in the vehicle control strategy.

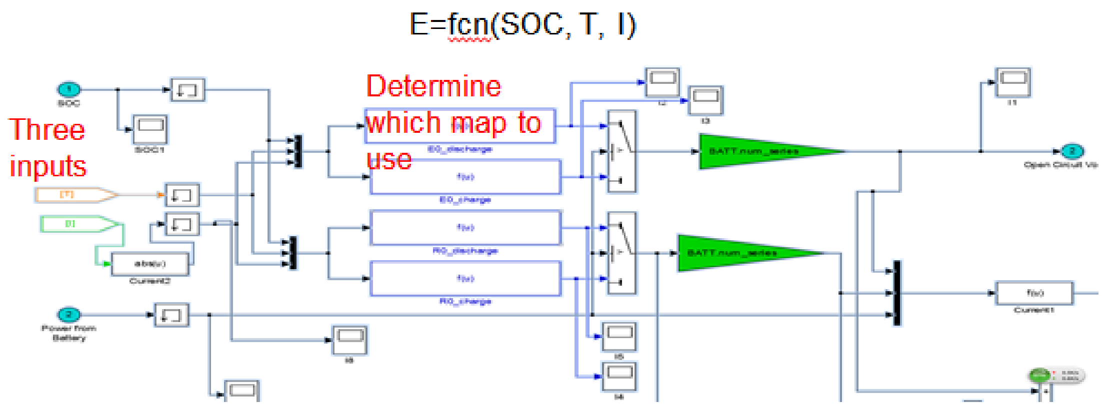


Figure. 16 Simulink model of battery pack

As is required, a thermal model is added in our vehicle, which is shown in the following picture. It is similar to the one in homework_4_task_1. The inputs are internal resistance and the current.

3. Control Strategy

3.1. 1. ECMS

Equivalent Consumption Minimization Strategy (ECMS) is an energy management method trying to minimize instantaneous energy consumption by finding the best torque split between motor and engine. One of the advantage of this method is it find the instantaneous optimal solution instead of global optimal, further driving information is not need.

$$min\left[\int \dot{m}_f\,(t)dt\right] \rightarrow \int min\,[\dot{m}_f(t)]dt$$

Steps in ECMS are as follows:

1. Discretization:

At a given torque request T_{req}, a set of combination of engine torque T_{ice} and motor torque T_{em} are generated. T_{ice} is a vector of variables from 0 to the maximum torque.

$$T_{em} = T_{request} - T_{ice} \quad (4.1)$$

2. Calculation Equivalent fuel consumption of electrical motor:

$$m_{em\_eq} = f_{penalty} * \left(\frac{\gamma}{s_{chag}} + \frac{1-\gamma}{s_{dischg}}\right) * \frac{em_{trq} * em_w}{QHLV} \quad (4.2)$$

$$\gamma = \frac{1 + sign(em_{trq})}{2} \quad (4.3)$$

γ is a factor depend on whether the motor is powering or breaking. When motor torque is negative $\gamma = 0$, when the torque is positive $\gamma = 1$.

The factor s_{chag} and $s_{dischag}$ are define as:

$$s_{chag} = \eta_{ch}\, w \quad (4.4)$$

$$s_{dischag} = \eta_{disch}\, w \; (4.5)$$

η_{ch} and η_{disch} is the efficiency of the electric motor at the operating point. As the efficiency of an electrical motor is much higher than an engine, the method tends to use more electric motor. A weight w is added to penalize on the use of electric motor. Here we set w =0.5.

$f_{penalty}$ is a SOC based penalty function is added. It penalizes battery usage when SOC are low and encourage battery usage when SOC are high. It is defined as:

$$f_{penalty} = \frac{1 - {x_{soc}}^3}{2} \quad (4.6)$$

The advantage of cubic function on linear function is that it remains relative constant when the value is in the middle of the range and the value changes sharply when it nears the upper and lower boundary. It can help battery SOC to sustain in the middle range.

Here we use x_{soc} instead of SOC. It is the mapping of maximum and minimum SOC between -1 and 1. It is defined as:

$$x_{soc} = \frac{SOC - (SOC_H + SOC_L)/2}{(SOC_H - SOC_L)/2} \quad (4.7)$$

3. Find the optimal torque split:
   The equivalent fuel consumption is
   $$m_{eqv} = m_{ice} + m_{em_{equ}} \quad (4.8)$$
   The optimal torque split is the point has the minimal equivalent fuel consumption.
   $$\tilde{T}_{em} = \{T_{em} \,|\, \min(\, m_{eqv})\} \quad (4.9)$$

3.2. Pre-computed Lookup Table:

Optimizing the torque split all the time is a very computational demanding task for vehicles' ECU. To reduce the computational cost, a lookup table is pre-computed. The ECU only needs to lookup the table to acquire the optimal torques split. The lookup table consists of 4 dimensions: engine speed, torque request, x_{soc} and gear selection. The output of the table is the torque request for the electric motor.

The figure below shows the change of motor torque demand as SOC changes from low to high. We can see less torque from the motor is requested when SOC is low. This is due to the penalty function penalize motor usage on low SOC.

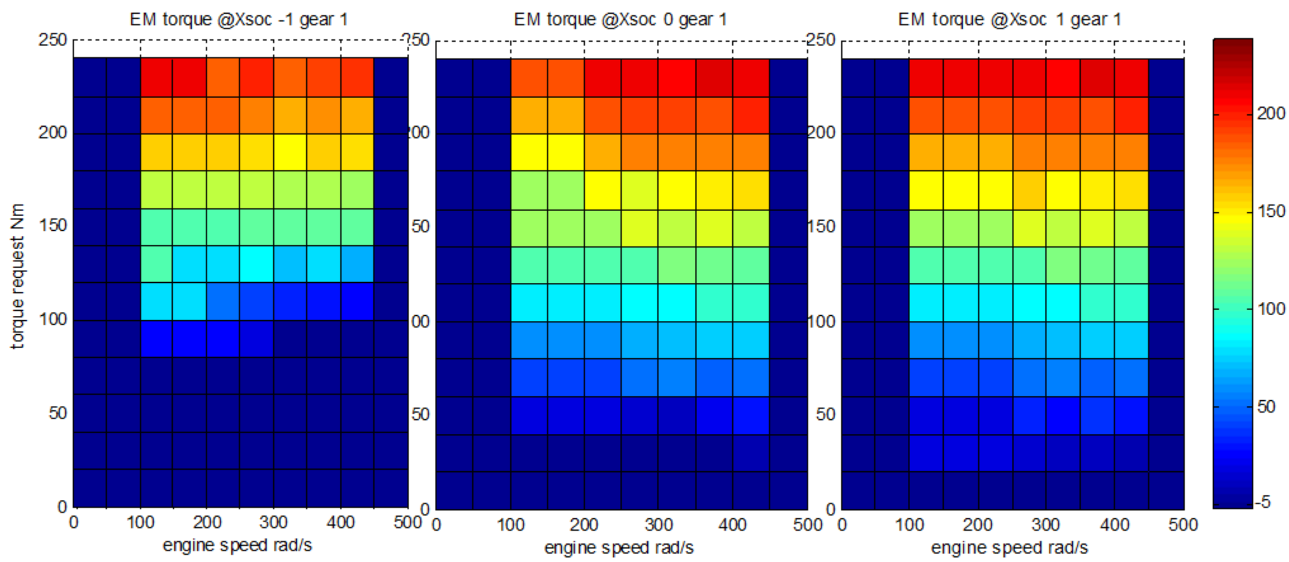


Figure. 17 Electric motor torque request under different SOC

3.3. Simulink Implement

The Simulink implemented of this control strategy is shown below. The input of this model is acceleration and brake pedal position. The output is engine and motor torque request. When acceleration pedal is pressure, the total torque request goes to the torque split subsystem. The optimal torque split is found through a lookup table.

There is also a sport model. When it is active, the controller just use maximum torque engine and motor can provide and do not consider the fuel economy.

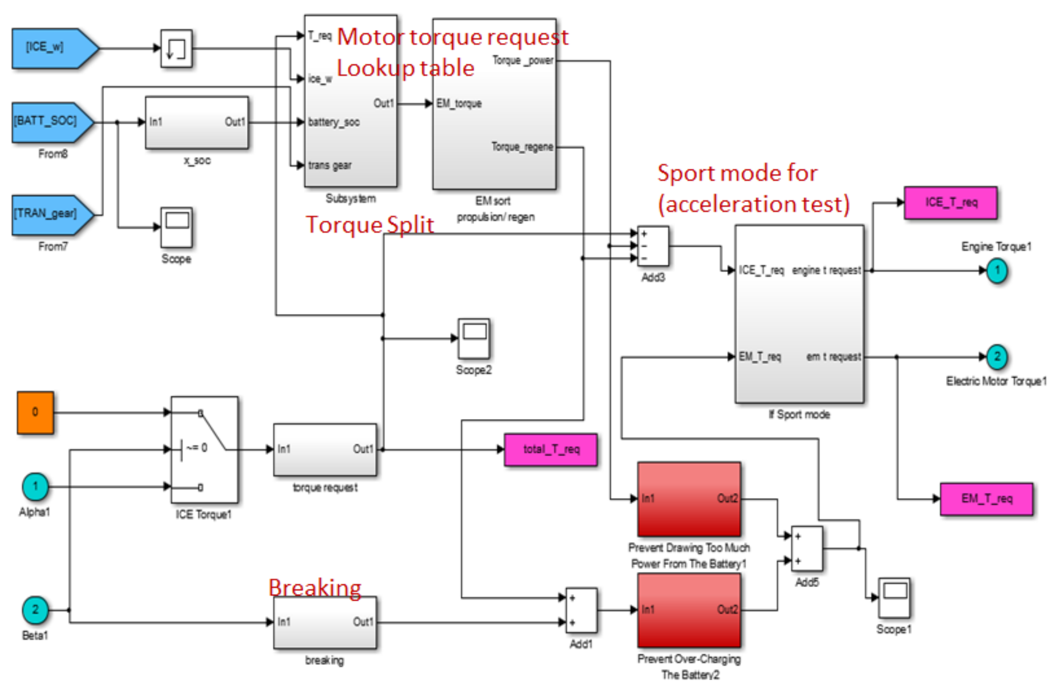


Figure. 18 Simulink model of control strategy

4. Simulation results

4.1. The results of FUDS:

a. A plot of the vehicle speed as a function of time (desired and actual)

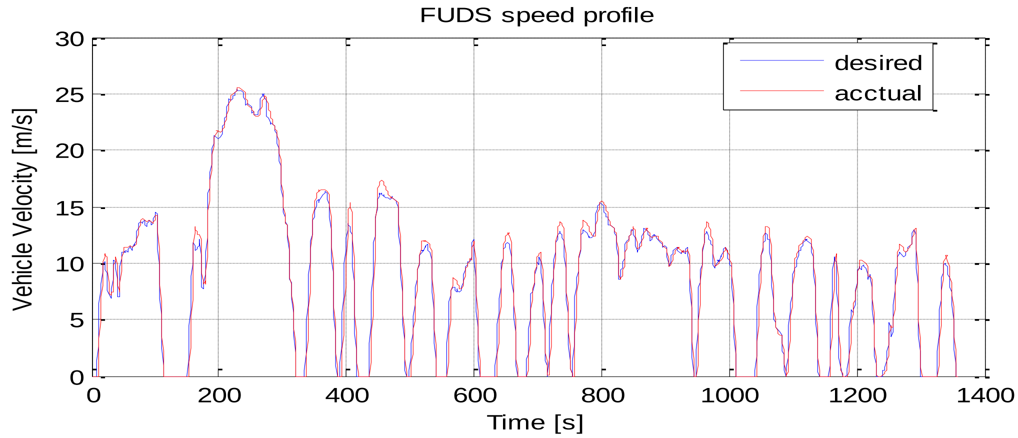


Figure. 19 desired and actual speed profit of FUDS cycle testing

We can see that the two velocity profiles matches well, which is what we want.

b. A plot of the engine RPM as a function of time

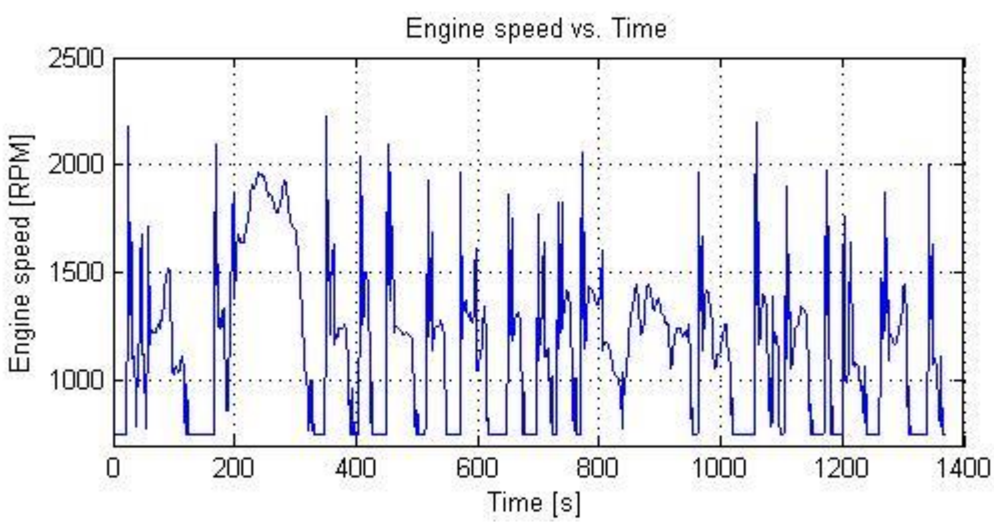


Figure. 20 Engine speed vs time on FUDS cycle

c. A plot of the engine torque as a function of time

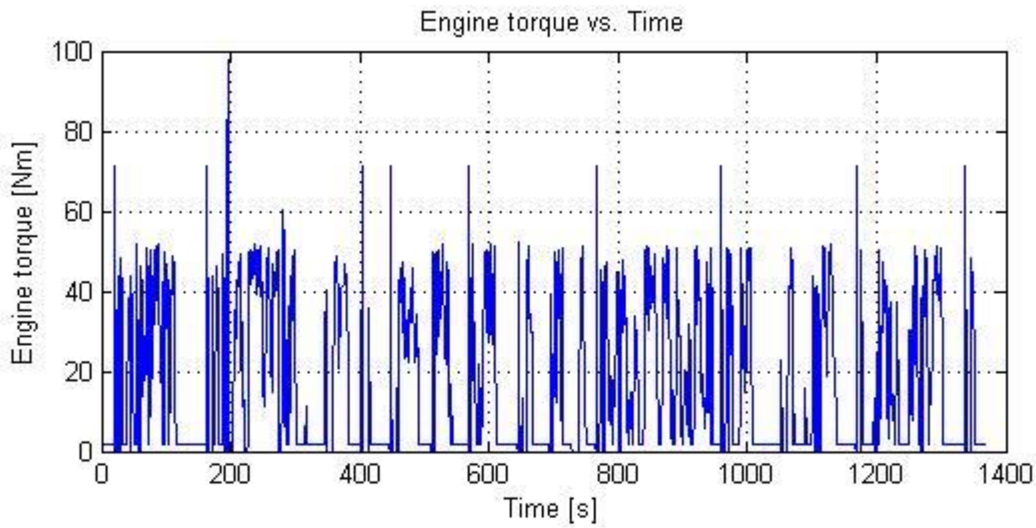


Figure 20 Engine torque vs time on FUDS cycle

We can see from the engine torque figure that most of the engine output torque is below 50 Nm. In order to improve the engine efficiency, we scale down the engine to 1.3L.

e. A plot with the engine efficiency map in the torque/speed plane with dots or crosses for all the operating points of the engine during the drive cycle

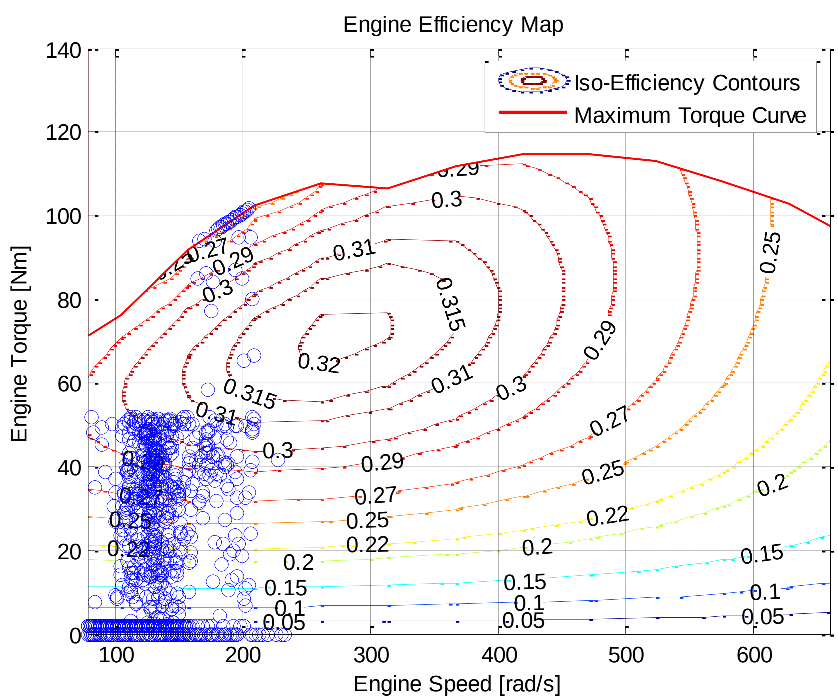


Figure 20 Engine operating points on FUDS cycle

From the above efficiency figure, we can get that most of operating points locate at the efficiency range of 0.25~0.31, which is relatively high for SI engine. There are several reasons why they don't locate right at the highest efficiency point for each engine speed. First, there are only four gear ratios, CVT will give the optimal solution. Second, engine fuel consumption is combined with electric motor. May be the engine fuel consumption is not the best. When we also consider the electric motor equivalent fuel consumption, the combination of the engine and EM fuel consumption is the best according to the ECMS control strategy.

f. A plot of the electric motor torque as a function of time

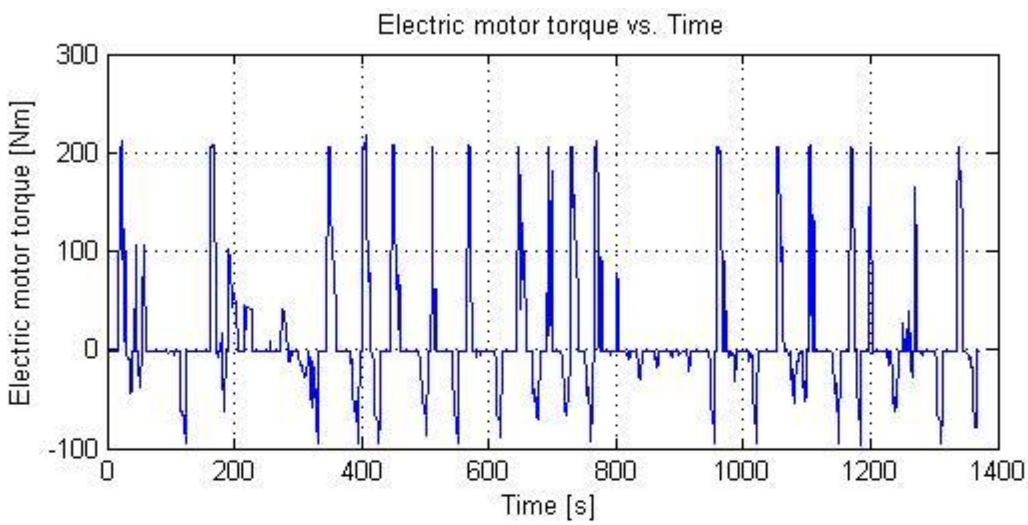


Figure 21 Electric motor torque vs time on FUDS cycle

Even though the peak positive electric motor torque is greater than the peak negative torque. The time elapse for the negative torque is longer than the positive torque, which results in the exit SOC (0.73) to be greater than the initial SOC (0.65).

g. A plot of the electric motor speed as a function of time

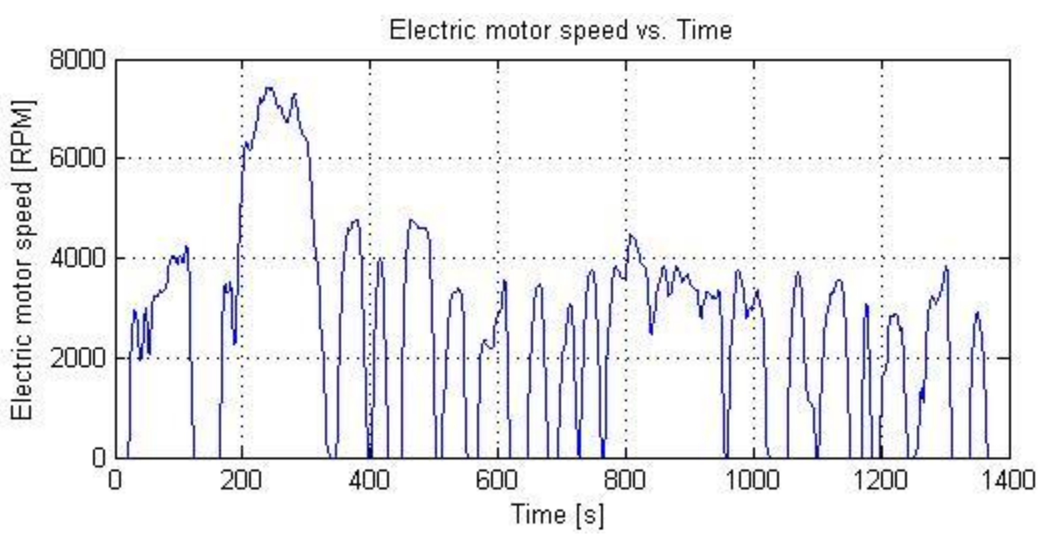


Figure. 22 Electric motor speed vs time on FUDS cycle

Because electric motor is connected to the rear wheels all the time, the electric motor speed profile is the same as cycle velocity profile.

h. A plot of the battery voltage and current as a function of time

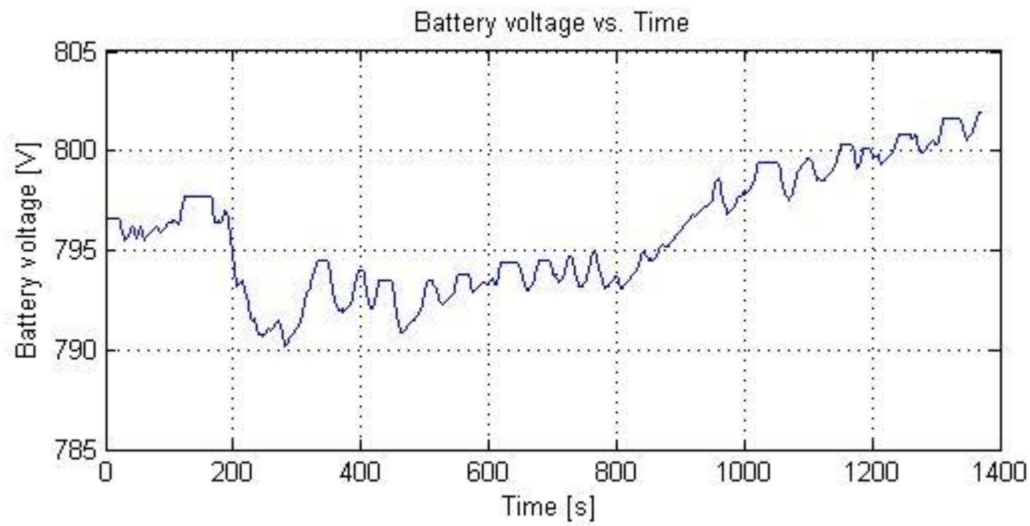


Figure. 23 Battery voltage vs time on FUDS cycle

The Battery voltage can be explained by SOC trend. Because it is from the lookup table and the input is the SOC. Generally, the greater the SOC is, the higher the battery open circuit voltage.

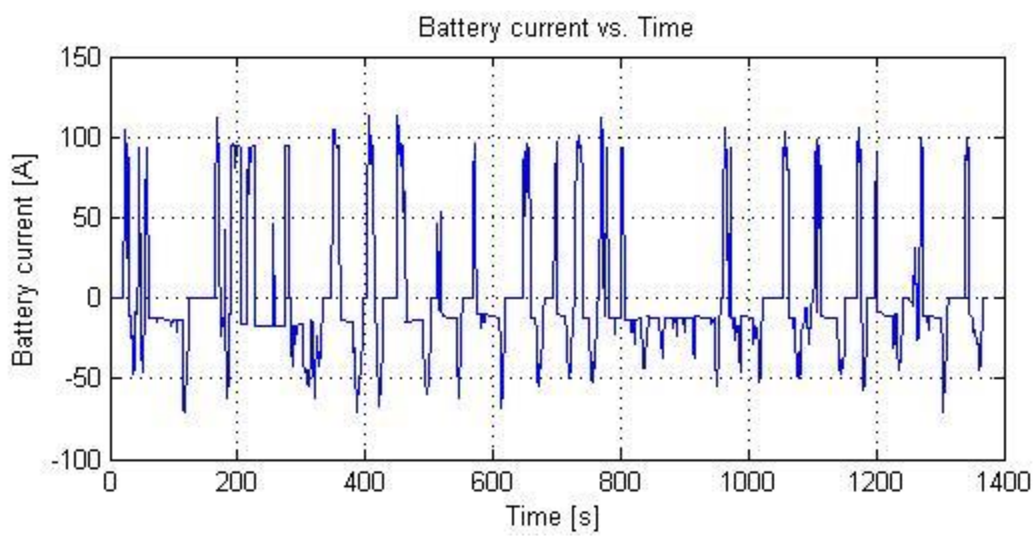


Figure. 24 Battery current vs time on FUDS cycle

i. A plot of the battery SOC as function of time and a plot of the Peukart curve.

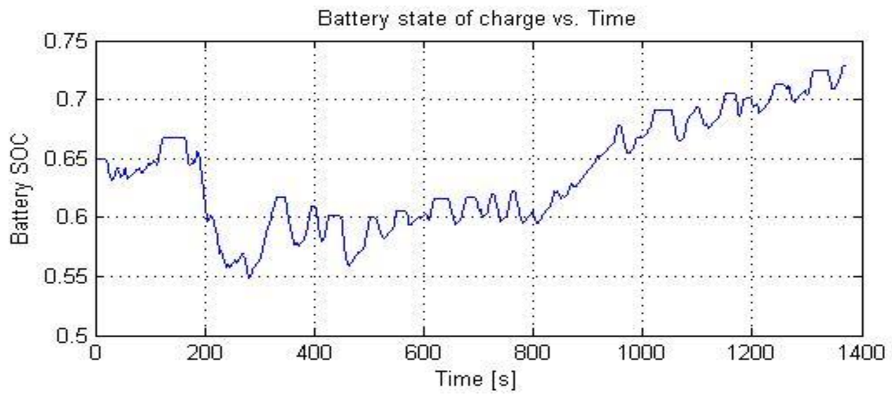


Figure. 25 Battery SOC vs time on FUDS cycle

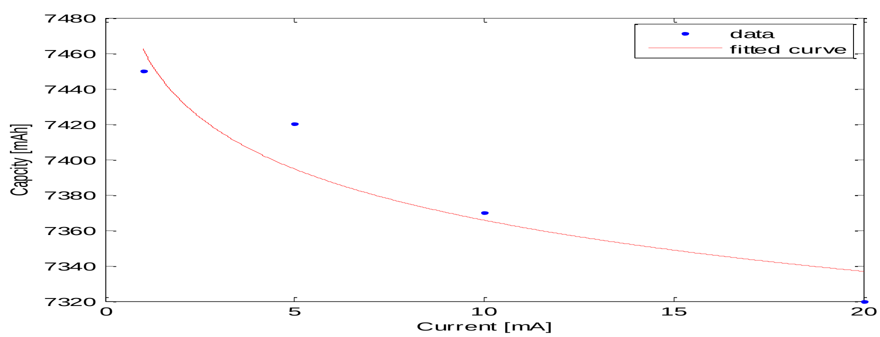


Figure. 26 Peukart curve fitting and original date.

j. plot with the electric motor efficiency map in the torque/speed plane with dots or crosses for all the operating points of the engine during the drive cycle

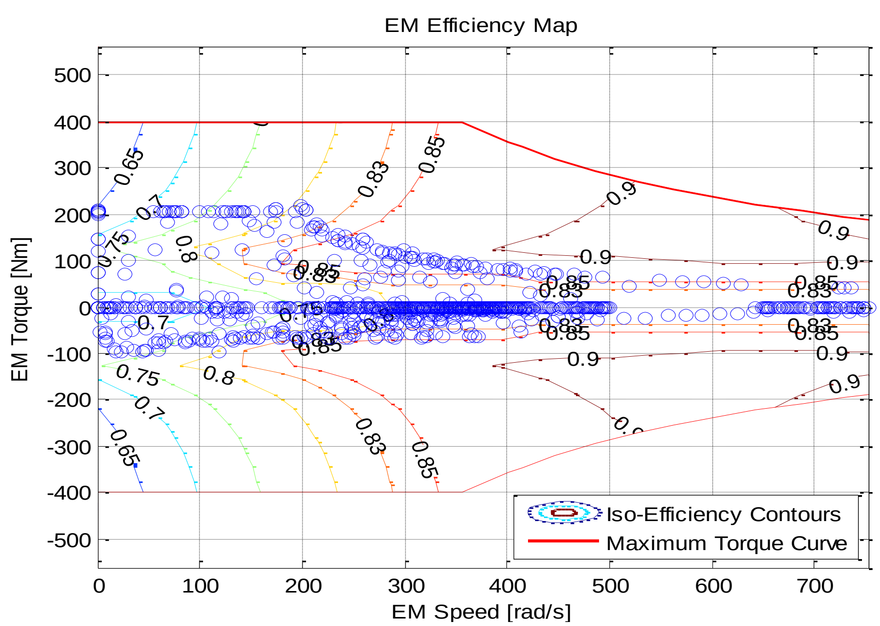


Figure. 27 Electric motor operating points

We can see from the electric motor efficiency map that the operating points not always locate at the optimal place at certain speed. The reason is that the optimal fuel consumption is the combination of engine and electric motor. Sometime, the control strategy will sacrifice the EM efficiency to improve engine efficiency, which will bring the best fuel consumption for the hybrid vehicle.

4.2. Acceleration testing:

II) Determine the vehicle effective top speed

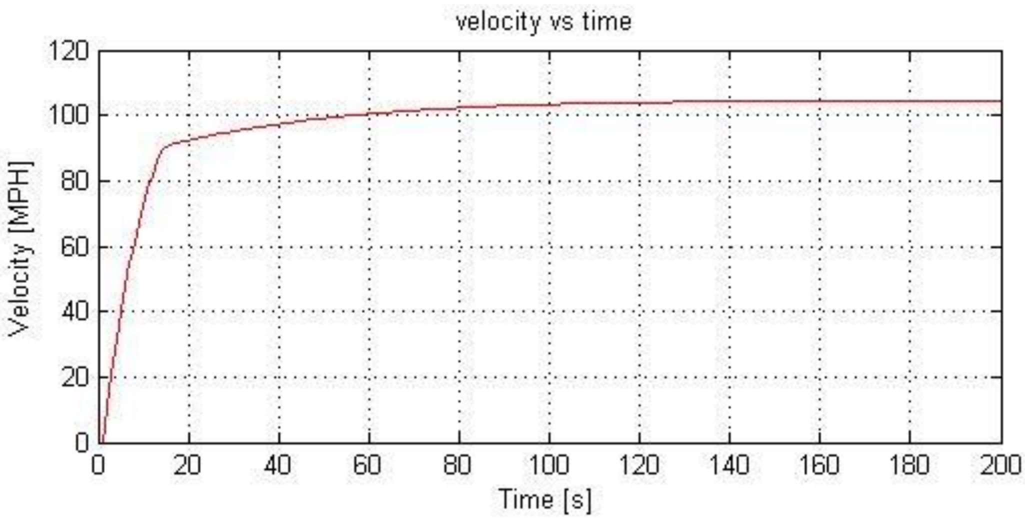


Figure.28 Velocity profile on accelerating test

We can see form the figure that the effective top speed is nearly 105 mph, which meets the demand 100 mph. In order to meet this demand, engine sizing is operated here. With larger engine displacement, higher top speed can be achieved. Finally, we meet the top speed demand with the 1.3L engine, which is also related to the MPG.

III) Show your all-electric range results under the UDDS cycle.

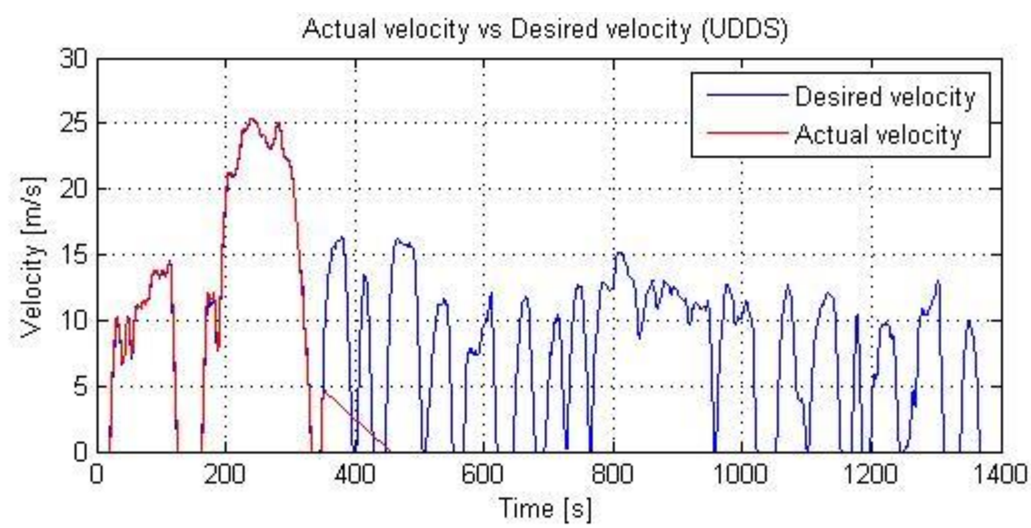


Figure.29 All-electric testing speed profile under UDDS cycle

For the all-electric range, the initial SOC is 0.65 and the SOC low red line is 0.2, which is given by considering the protection of battery and improvement of range.

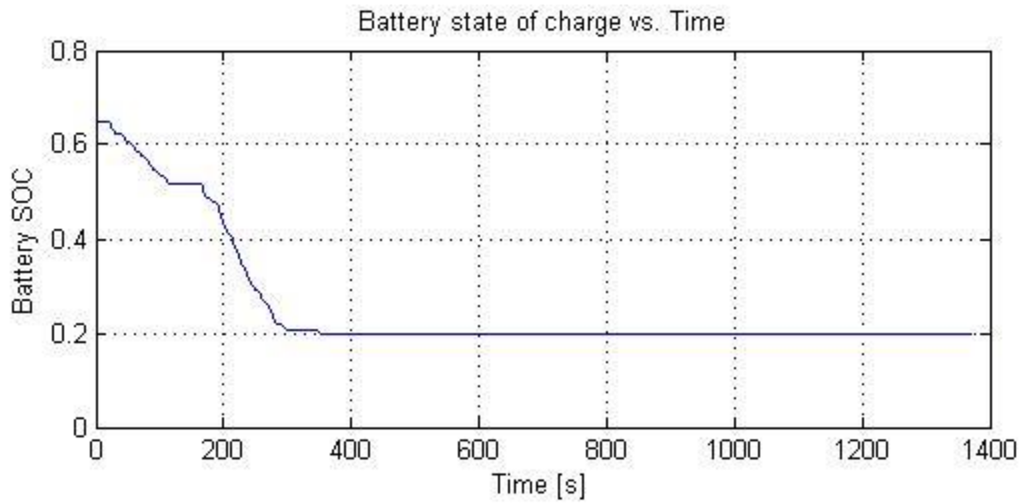


Figure.30 Battery state of charge vs time on All-electric testing

IV) Consider the FUDS, FHDS, US06, cycle_4.87miles and cycle_10.6miles repeated several times. What is your fuel economy after 50 miles? And after 100 miles? Compare and discuss the results.

Driving cycles	Distance per cycle (miles)	MPG	
		After 50 miles	After 100 miles
FUDS	7.55	60.60	61.35
FHDS	10.26	56.96	57.06
US06	8.1	22.98	23.14
cycle_4.87 miles	4.87	55.92	56.06
cycle_10.6miles	10.6	52.83	53.49

As we can see that for the certain driving cycle, MPG for the 50 miles is smaller than that for 100 miles, which can be explained by the initial SOC for each cycle. With higher initial SOC, the MPG will go higher, because more energy is available in the battery. For the first 50 miles case, initial SOC is 0.6. For the second 50 miles, initial SOC is the exit SOC for the first 50 miles, which is generally larger than 0.6 from the results of the simulation. For the different cycle, MPG are different. FUDS has the highest MPG because there are lots of conditions to brake. US06 has the lowest MPG because of the rapid change of velocity profile. The other three cycles also have high MPG, which are smaller than that of FUDS a little bit.

V) Analyze how changes in the control strategy parameters affect the results in IV). Do you have to adjust your control strategy parameters for every cycle type or not to achieve best fuel economy?

One of the tuning factors is the penalty weight w for electric motor as shown in equation 4.4 and 4.5. Since the efficiency of a motor is much higher than engine, the method tends to use more electric motor. The penalty weigh is use to limited use the electric model.

The other tuning factor is the torque limited when using engine to recharge the battery. The goal is to keep the SOC sustain in the range. If SOC at the upper limit, break energy cannot be recuperated. On the other hand if SOC is on the lower limited, the use of electric motor would be limited. By trying different parameter the lower torque limit of -3 Nm has the best result.

VI) For the acceleration test case, calculate the following drivability and performance metrics:

a. Top speed of the vehicle
b. 0-60 MPH time
c. ¼ mi time and exit speed
d. 0-20, 20-40, 30-50, 50-70 MPH times

Generate a plot with the engine map in the torque/speed plane and the motor map in the torque/speed plane with dots or crosses for all the operating points during the ¼ mile run. What do you expect and why? Discuss if and how the performance metrics are affected by the battery selection.

We can see from the following two figures that all the operating points for both of engine and electric motor runs at the maximum torque curve, which means no matter what speed the vehicle runs, maximum torque is used to push the vehicle forward. This result is right the same as what we want it to be. Because if we want to accelerate fast, we need to increases the acceleration as much as we can. For the engine and electric motor, maximum torque output at each speed can ensure the maximum acceleration. Therefore, the acceleration test results match what I expect. Battery selection

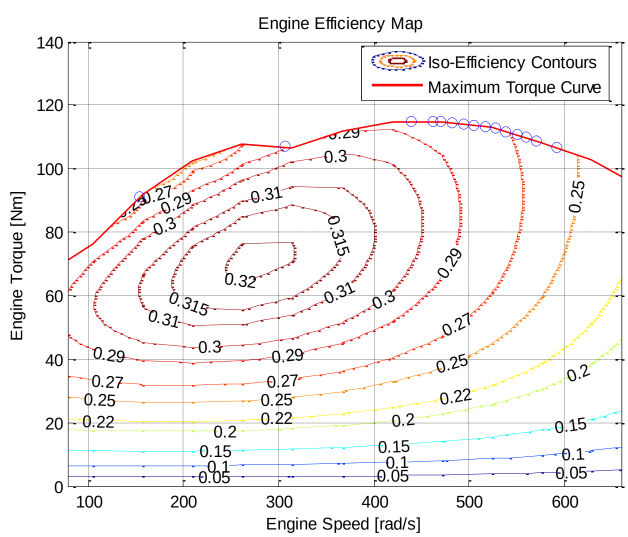


Figure.31 engine operating points on accelerating test

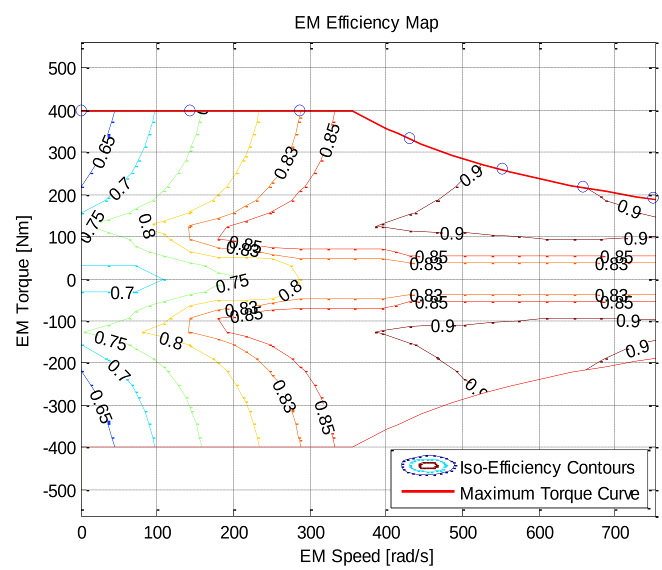


Figure.32 motor operating points on accelerating test

As we change the cell number from 50 to 150 to 250, the performance parameters are given in the following form. The most sensitive parameter is the 0-60 acceleration time. As the increase of cell number, the 0-60mph goal is met. Top speed does not change, because at the end of acceleration test, all the power is from engine Battery SOC reach the bottom line. For the 30-50mph acceleration time, the time for the 50 cells case is as twice as the other two cases. The reason is that the number of cells limit the energy capacity of the battery. All the electricity runs out during the 50-70 mph acceleration for the case of 50 cells, which the other two cases have enough energy capacity to power the hybrid vehicle accelerate during this process. As the increase of velocity, the same situation occurs at the case of 150 cells, when comparing the 250 cells and 150 cells acceleration time in the process of 50-70 mph. Other several parameters do not change significantly.

Acceleration test (Variable battery cells)			
Cell number	250	150	50
Top speed (mph)	105	105	105
0-60 mph(s)	8.3	11.2	15.3
0-20 mph (s)	3	2.9	2.8
20-40 mph (s)	2.2	2.1	2.7
30-50 mph (s)	2.5	2.6	6.3
50-70 mph (s)	10	12.9	13
1/4 mi time	18.3	18.9	20.2
1/4 mi exit spd	71.7	69.2	65.8

VII) What is your combined MPG? Are you able to meet all the vehicle specification requirements? If not explain which specifications you were not able to meet and provide and explanation.

Combined MPG:

$$MPG_{combined} = \frac{1}{\frac{0.45}{MPG_{highway}} + \frac{0.55}{MPG_{city}}} = \frac{1}{\frac{0.45}{56.4} + \frac{0.55}{54.42}} = 55.29 > 34.6$$

All the vehicle specification requirements are meted, including 2020 CAFE target for LDT, top speed, 0-60 mph time, brake energy recovery, 350 miles range and no plug-in.

5. Summary

By downsize the engine and use engine and electric motor combined when big torque is need, our vehicle is able to achieve requirements on both and fuel economy and acceleration. The relatively small engine is to ensure a high efficiency during most of the driving cycle. But it can’t be too small, the effective top speed depends on the engine power. Because at the end of acceleration test, the hybrid vehicle will deplete the electricity in the battery and the effective top speed have to rely on the engine power. The big electric motor and packages of battery cells are to provide enough boost during accelerating when high torque and energy are needed. At last, the combination of 400Nm electric motor and 250 cells meet the 0-60 mph acceleration requirement. Some specifications of powertrain component s are listed in the table below.

Specifications:

Motor specifications	
Max Hp	143 Kw
Max Torque	400 Nm (0-357 rad/s)
Radius	57.6 mm
Length	392 mm

Battery pack	
Total battery capacity	1750 Ah
Max power	187 Kw
Battery cell weight	175 kg
Number of cells	250

Engine specs	
Max power	64.5 kW @ 6000 RPM
Max Torque	115 Nm @ 4400 RPM
Displacement	1.3 L
Bore	72.1 mm
Stroke	79.4 mm

Vehicle weight	
Curb weight	1300 kg
Motor	107 kg
Battery	175 kg
Driver	75 kg
Total	1636

Testing results:

Acceleration test	
Top speed	103 mph
0-60 MPH	8.3s
0-20	3s
20-40	2.2s
30-50	2.5s
50-70	10s
1/4 mi time	18.3s
1/4 mi exit spd	71.7mph

Fuel economy test	
Cycles	MPG
UDDS	54.42
HWFET	56.40
combined	55.29
US06	21.34
Cycle4.87 miles	55.86
Cycle10.6 miles	48.70

Appendix

Engine scaling (refer 'Group3_Enging_Scaling.m')

Electric motor scaling (refer 'Group3_EM_Scaling.m')

Battery sizing (refer 'Group3_Battery_Sizing.m')

Control strategy (refer 'Group3_ECMS_control_strategy.m')