# ECE 51018 HYBRID ELECTRIC VEHICLES

## Project 1: Analysis of Parallel Hybrid Electric Vehicle

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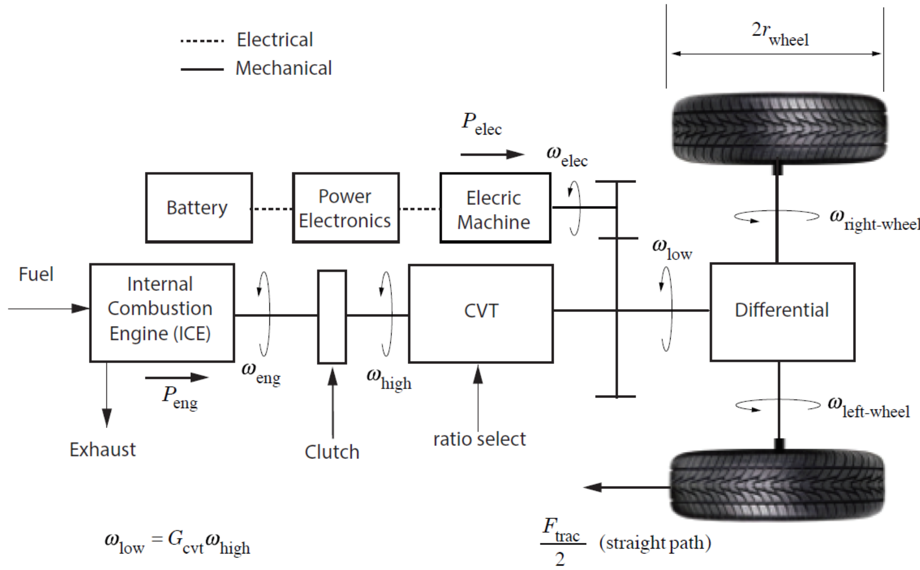
## Problem Description

In this project, we are studying the post-transmission, parallel hybrid electric vehicle architecture [1]. The objective is to analyze the performance of this vehicle architecture, shown in Figure 1.




$$\omega_{\text{low}} = G_{\text{cvt}}\omega_{\text{high}}$$

$$\omega_{\text{right-wheel}} = \omega_{\text{left-wheel}} = \omega_{\text{wheel}} = G_{\text{diff}}\omega_{\text{low}}$$

$$v_{\text{veh}} = r_{\text{wheel}}\omega_{\text{wheel}}$$

$$\omega_{\text{low}} = G_{\text{elec}}\,\omega_{\text{elec}}$$

**Figure 1. Post-Transmission Parallel Hybrid Electric Vehicle**

The goal is to develop a MATLAB Simulink model that estimates parameters such as engine/electric motor speed; engine/electric motor power; traction force, power, torque; mpg; battery state of charge; etc. given a drive schedule. The vehicle parameters are given in Table 1.

**Table 1. Summary of vehicle parameters**

| **Parameter** | **Value** | **Parameter** | **Value** |
|---|---|---|---|
| Vehicle empty mass (w/o battery, pax) | 1746 kg | Aerodynamic drag coefficient | 0.35 |
| Driver mass | 70.00 kg | Frontal area | 1.93 $m^2$ |
| Battery mass | 43.48 kg | Energy storage subsystem capacity | 2 kWh |
| Wheel radius | 0.2794 m | Energy storage subsystem round-trip efficiency | 0.8 |
| Electric machine gear ratio | 1 | Minimum engine speed | 1000 rpm |
| Transmission gear ratio (min) | 0.5 | Minimum engine power | 10 kW |
| Transmission gear ratio (max) | 4.5 (US06) | Maximum engine power | 85 kW |
| Differential gear ratio | 0.268 | Initial SOC | 0.5 |
| Rolling resistance coefficient | 0.015 | Gravimetric density of gasoline | 0.75 kg/liter |

## Assumptions

*Drive Cycles*

To estimate vehicle performance parameters, we need to have the data on its drive schedule. A drive schedule is a vehicle speed versus time graph showing when a vehicle is at rest, when it is at its maximum velocity, when it is accelerating or decelerating, etc. In this project, we use drive cycles that are conventionally used by the EPA for testing different driving environments such as in city, highway, Los Angeles, etc. The four drive cycles used in this study are shown in Figure 3 and described below. The cycle repeats itself after each cycle time. There are no grade forces.

1. **US06 (596 sec.):** very rigorous drive cycle in that the speeds go all the way to 80 mph and down to 0 in seconds and is used by the EPA for studying the extended loads on a vehicle
2. **FTP75 (1874 sec.):** drive cycle matches the speed profiles seen in an urban area (30-55 mph). The vehicle can stop often due to the traffic signals, which is observable in Figure 3. One more noticeable pattern is that the vehicle tends to drive between 0-20 mph, while spending some time between 20-40 mph range.
3. **HWFET (765 sec.):** drive cycle matches the speeds seen on a highway (55-60 mph). The vehicle rarely comes to a full stop, but a few decelerations/accelerations exist.
4. **LA92 (1435 sec.):** drive cycle of Los Angeles. The vehicle stops frequently, just like in FTP75. Unlike FTP75, LA92 spends considerable time in speed ranges of 20-40 mph.

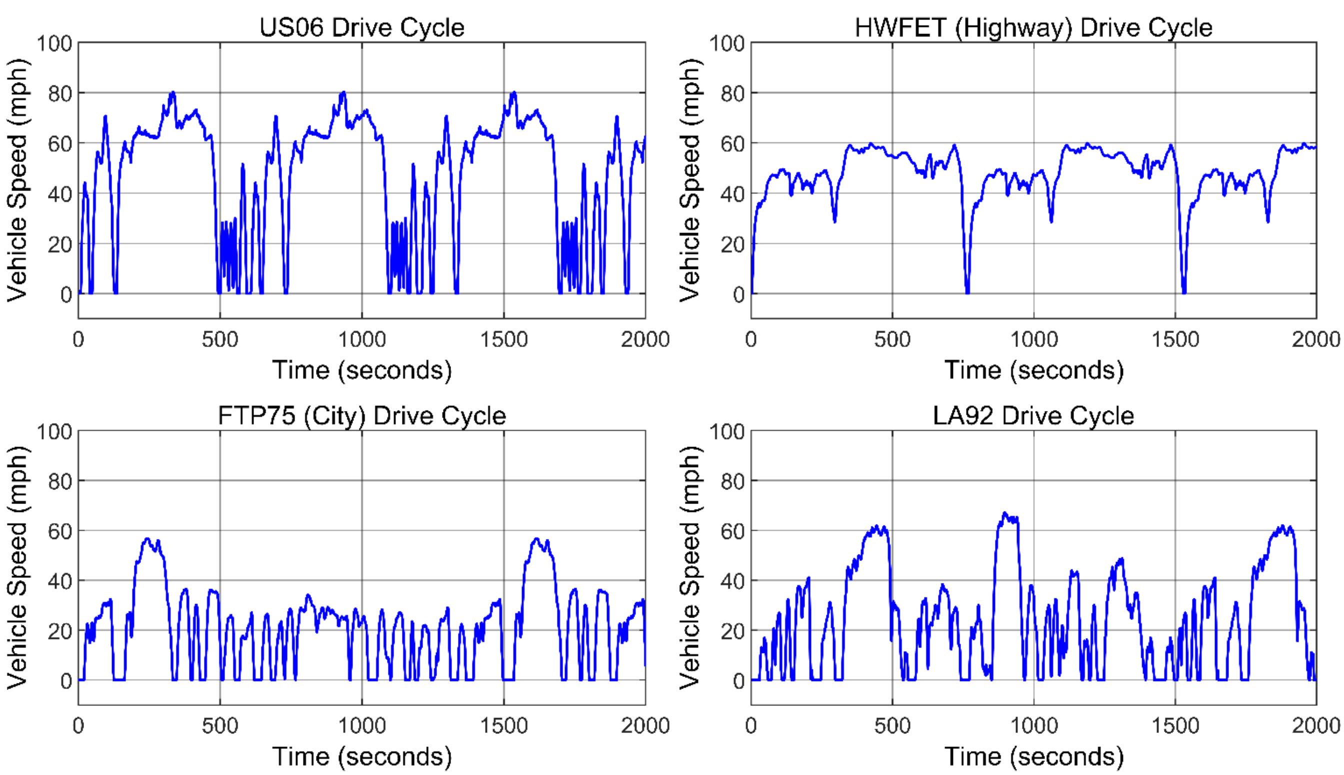



**Figure 3. Drive cycles of various types, showing vehicle speed versus time**

*Internal Combustion Engine Operating Conditions*

The Internal Combustion Engine (ICE) is assumed to be always operating at the optimal brake-specific fuel consumption (BSFC) line, shown in Figure 2.

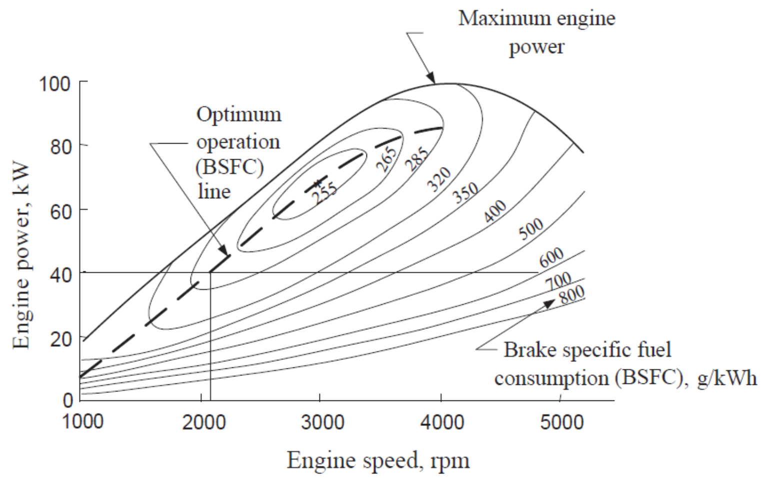



**Figure 2. Brake Specific Fuel Consumption (BSFC) showing the Optimal Operation Line**

*Power Management Strategies*

Power management strategies are important for parallel hybrid electric vehicle. Unlike a series hybrid vehicle, parallel hybrid vehicle can be driven by either the Electrical Energy Storage System (ESS) or the Internal Combustion Engine (ICE) – independently if necessary – as shown in Figure 1. Hence, it is important to distribute the power from ESS and ICE in a balanced approach such that the battery State of Charge (SOC) is averaged around 0.50 in a long drive schedule. In this project, we incorporate 4 power management strategies, which are detailed below:

1. If the vehicle speed is less than a certain threshold, then only the ESS is used. This phase is called Electric Launch Mode. In this phase, the clutch is disengaged, so the Internal Combustion Engine (ICE) is not doing any work to rotate the wheels. The battery State of Charge (SOC) decreases.
2. If the vehicle speed is above the threshold but the Traction Power is less than the Engine Power, it would be inefficient to lower the Engine Power. Hence, the ESS is once again used to drive the wheels, but this time the clutch to the Internal Combustion Engine (ICE) is engaged. This phase is called All-Electric Mode. The battery State of Charge (SOC) decreases.
3. When the Traction Power is greater than the maximum Engine Power, the ESS is used to give boost to the vehicle. This phase is called the Electric Boost Phase. The battery State of Charge (SOC) decreases.
4. When the Traction Power falls between the minimum and maximum Engine Power range, and the vehicle speed is greater than the threshold, then the Internal Combustion Engine is used to drive the vehicle. The batteries are recharged if SOC is less than 0.5 and discharged if greater than 0.5, at a rate of 4kW.

**MATLAB Model**

The Free-Body-Diagram of the vehicle is simplified. There are no grade forces due to the assumption that the ground is always flat. The three forces acting on the vehicle are:

(1) Aerodynamic Drag Force ($F_{aero}$)
(2) Rolling Resistance force ($F_{rr}$)
(3) Accelerating Forces ($F_{accl}$)

The traction force ($F_{trac}$) is the addition of all three forces. The traction power ($P_{trac}$) is found by multiplying traction force by the vehicle speed. Traction power specifies the power that either the ESS or ICE needs to provide to drive the vehicle at those speeds. The Simulink file is also attached with this document under the file name, *Simulink_Model.slx*. A more complicated Simulink model used in this project is also attached under the file name, *Simulink_Model_Complicated.slx*. However, the top-level picture of the diagram is shown in Figure 3, which was taken from [1]. The Tractive Forces and Tractive Power plots are shown in Figures 4 and 5.

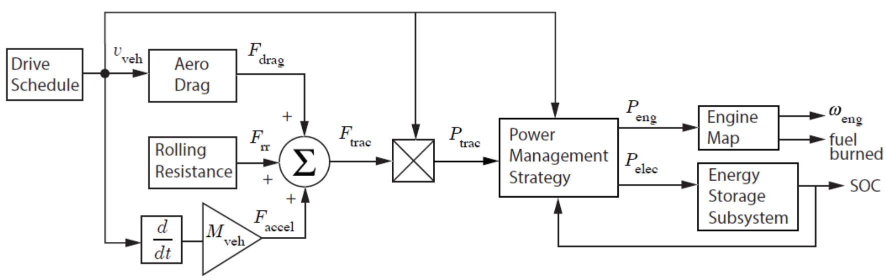



**Figure 3. Top-Level Simulink Block Diagram**

**Results and Discussion**

Tractive Forces of the drive cycles are shown in Figure 4. The maximum for US06 is around 6500N and minimum for US06 is around -5000N. On average the tractive force is less than 1000N. The maximum for FTP75 is around 3000N and minimum is around -2500N. On average the tractive force is less than 1000N. The maximum for HWFET is around 3000N and minimum is around -2500N. On average the tractive force is less than 1000N. The maximum for LA92 is around 5500N and minimum is around -6000N. On average the tractive force is less than 1000N.

Tractive Power of the drive cycles are shown in Figure 5. The maximum for US06 is around 100kW and minimum for US06 is around -50kW. On average the tractive power is around 20kW. The maximum for FTP75 is around 45kW and minimum is around -25kW. On average the tractive power around 0kW. The maximum for HWFET is around 40kW and minimum is around -40kW. On average the tractive power appears to be 0kW or less than 0kW. The maximum for LA92 is around 50 kW and minimum is around -100kW. On average the tractive force is slightly less than 0kW. The negative power means that the vehicle is dispersing the energy when it stops, or in this case, recharging the ESS.

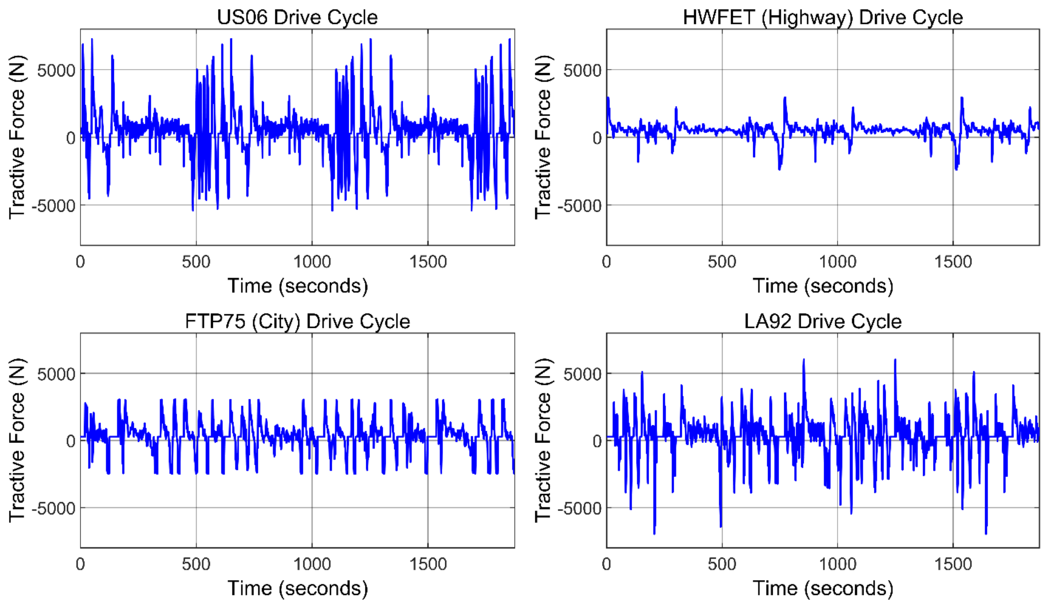



**Figure 4. Tractive Force versus Driving Time**

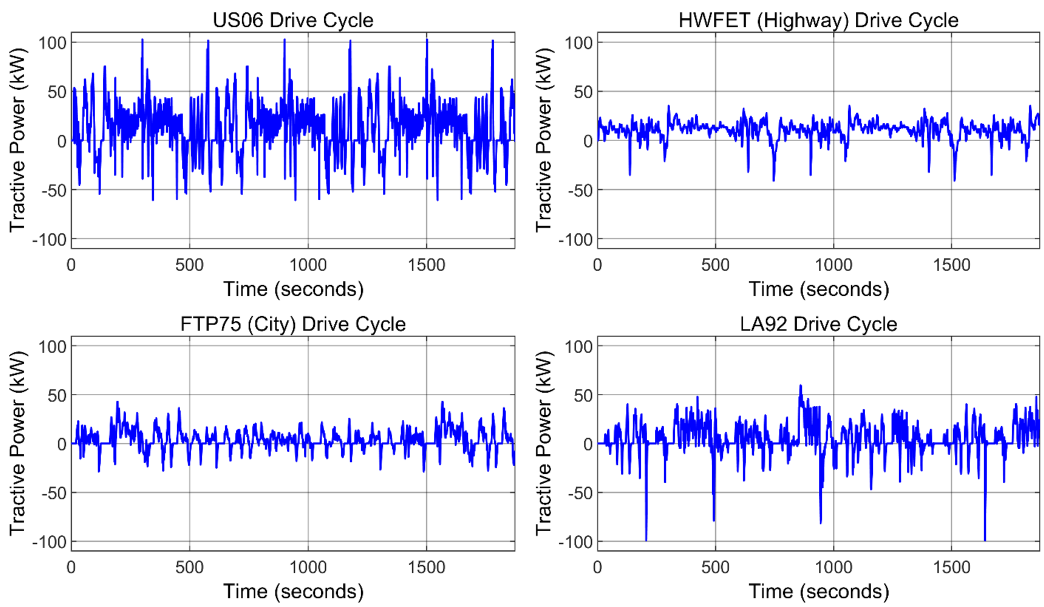



**Figure 5. Tractive Power versus Driving Time**

The engine speeds are shown in Figure 6. They appear to be under the reasonable limits. For US06, the maximum engine speed is 4000RPM. For FTP75, the maximum engine speed is above 2000 RPM. Note that there are many instances where engine speed is 1000 RPM because of how often the vehicle stops and uses Electric Launch Mode. For HWFET, the maximum is also around 2000 RPM. For LA92, the maximum engine speed is slightly less than 3000 RPM, but also notice how the engine speed is 1000 RPM when it stops. The 1000 RPM speed is the minimum engine speed of the vehicle.

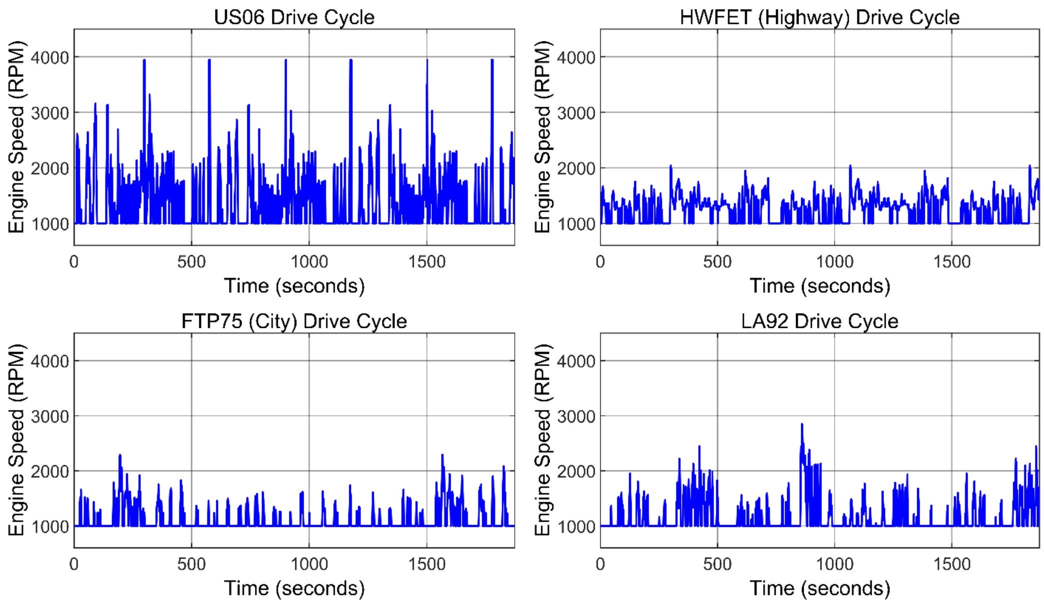



**Figure 6. Engine Speed (RPM) versus Driving Time (1874 seconds)**

The power supplied by the engine are shown in Figure 7. They appear to be under the reasonable limits. For US06, the maximum engine power is around 80kW. On average, the engine power is around 20kW. For FTP75, the maximum engine power is above 45kW. On average, the engine power is around 10kW. Note that there are many instances where engine power is 0kW because of how often the vehicle stops and uses Electric Launch Mode. For HWFET, the maximum is also around 40kW. On average, the engine power is around 10kW. For LA92, the maximum engine power is slightly less 65kW, but also notice how the engine power is 0kW when its under Electric Launch and All-electric Modes. On average, the engine power is around 15kW.

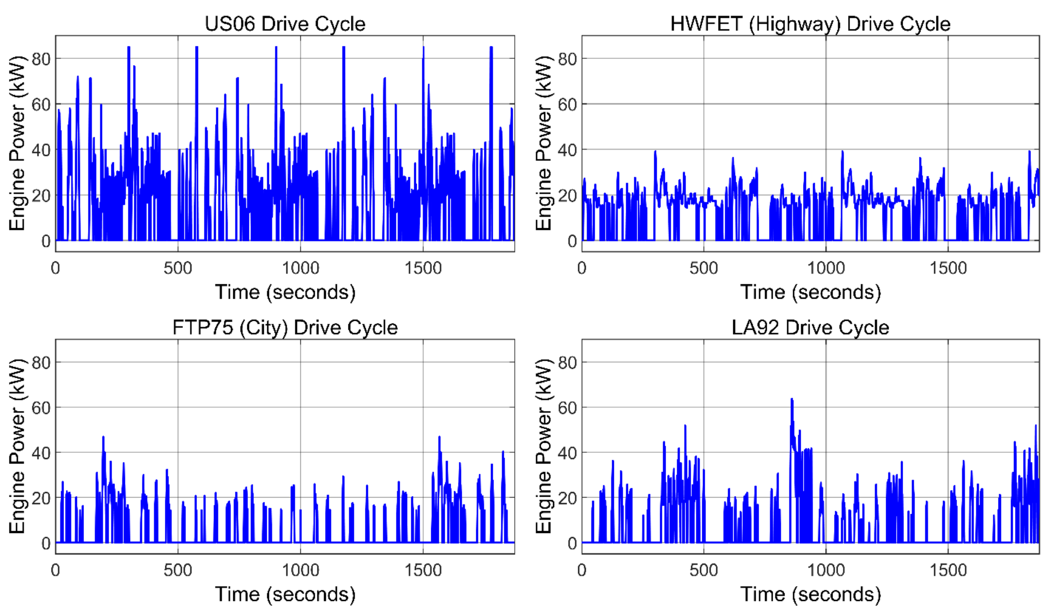



**Figure 7. Engine Power (kW) versus Driving Time (1874 seconds)**

The ESS speeds are shown in Figure 8. They appear to be under the reasonable limits. For US06, the maximum ESS speed is 4500RPM. For FTP75, the maximum engine speed is above 3000 RPM. Because the vehicle uses Electric Launch Mode and All-Electric Mode, the instances where the engine speed was 0 RPM is when the ESS is actively powering the drivetrain. For HWFET, the maximum is also around 3500 RPM. However, the ESS speeds are above 2000 RPM most of the drive. For LA92, the maximum engine speed is slightly less than 4000 RPM, but also notice how the ESS speeds are mostly between 0 and 2000 RPM.

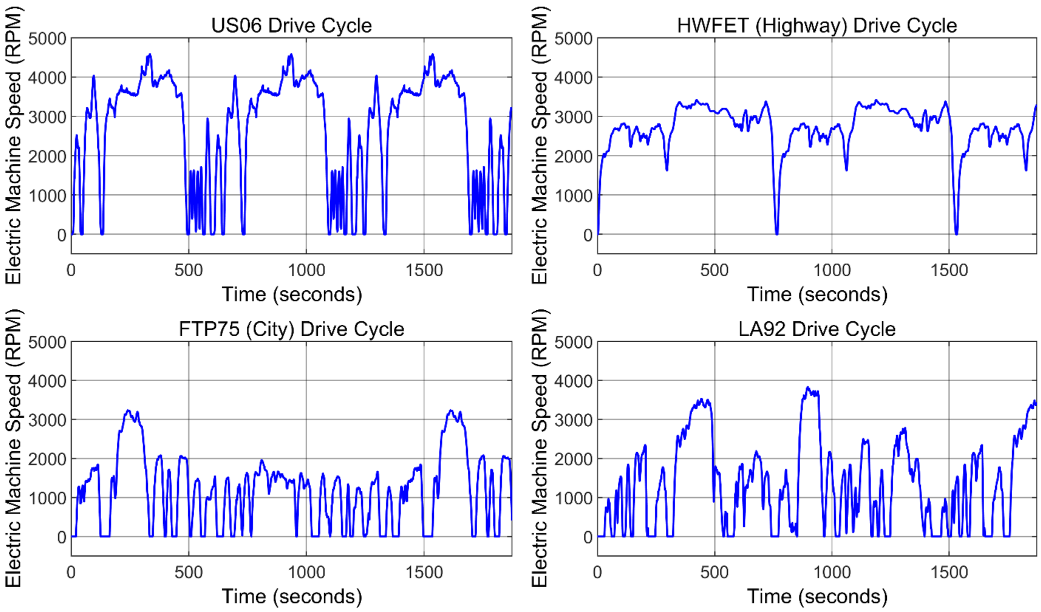



**Figure 8. Electric Machine Speed (RPM) versus Driving Time (1874 seconds)**

ESS Power is shown in Figure 9. The negative power means the ESS is recharging and the positive power means that the ESS is discharging. In the US06 cycle, the minimum ESS power is around -50kW and maximum around 20kW. For FTP75, the minimum is around -30kW and the maximum is around 10kW. For HWFET, the minimum is around -30kW and the maximum is around 10kW. For LA92, the minimum is around -100kW and the maximum is around 15kW. The negative power means that the vehicle is decelerating more often, losing power while braking.

ESS Torque is shown in Figure 10. The maximum and minimum torque values are misleading because whenever the vehicle stops, the torque goes to infinity, in both directions.

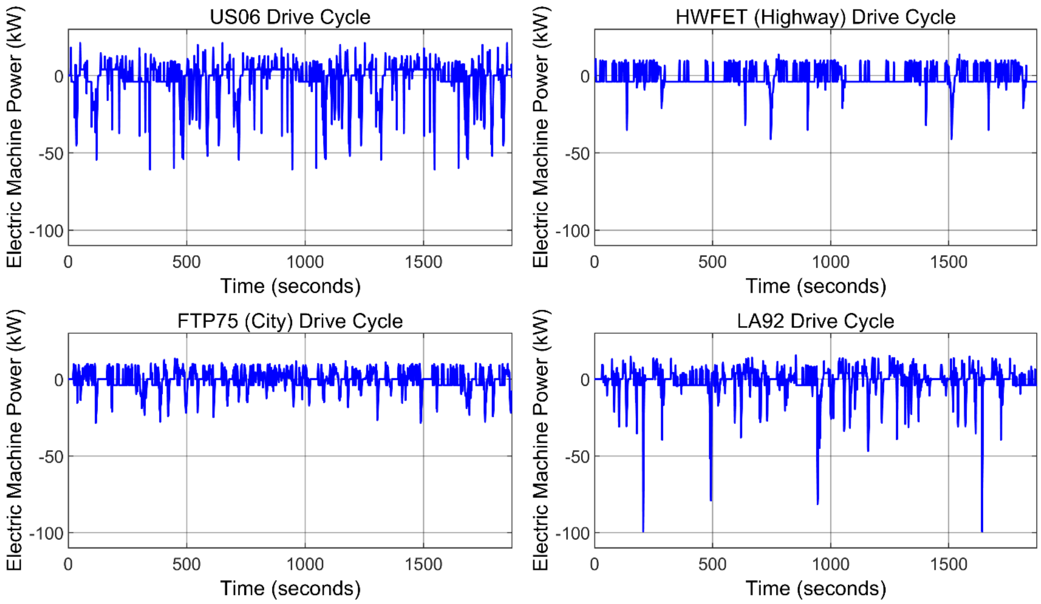



**Figure 9. Electric Machine Power (kW) versus Driving Time (1874 seconds)**

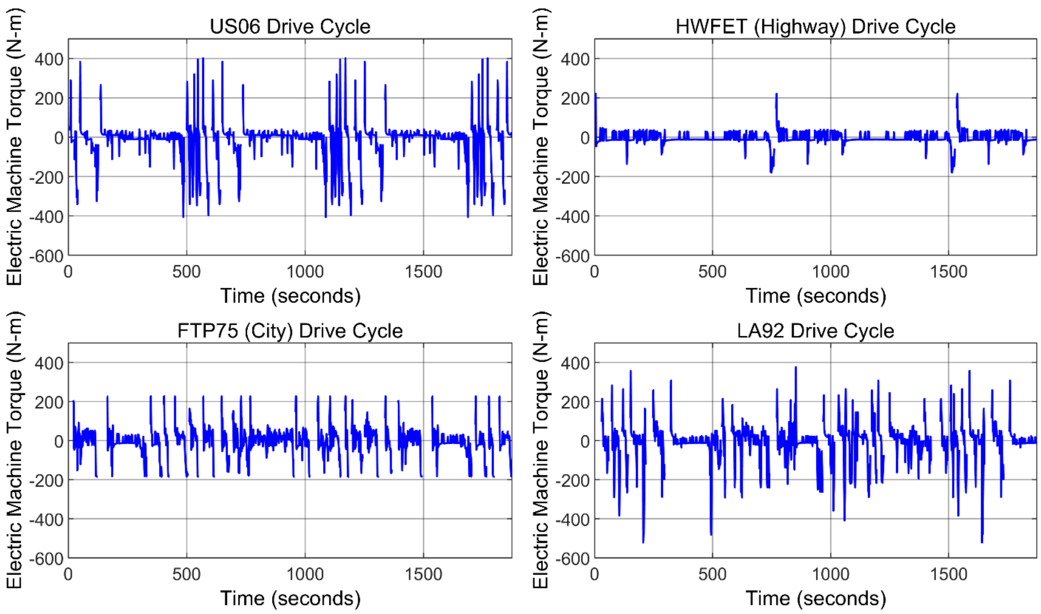



**Figure 10. Electric Machine Torque (N-m) versus Driving Time (1874 seconds)**

The State of Charge is shown in Figure 11. For US06, the maximum state of charge is around 0.65 and the minimum is slightly less than 0.5. Overall, the vehicle tries to stay at 0.5 state of charge. For FTP95, the maximum SOC is around 0.5 and the minimum is around 0.35. The vehicle SOC remains below 0.50. Because FTP75 is a city driving cycle, the vehicle is often in the All-Electric Mode or Electric Launch Mode due to stop and go driving conditions. For HWFET, the maximum SOC is also around 0.50 and the minimum is around 0.45. For US06, the maximum state of charge is around 0.55 and the minimum is slightly less than 0.5. Overall, the vehicle tries to stay at 0.5

state of charge. This could be due to LA traffic having many stop-go conditions, but when it is not, the power is produced by ICE.

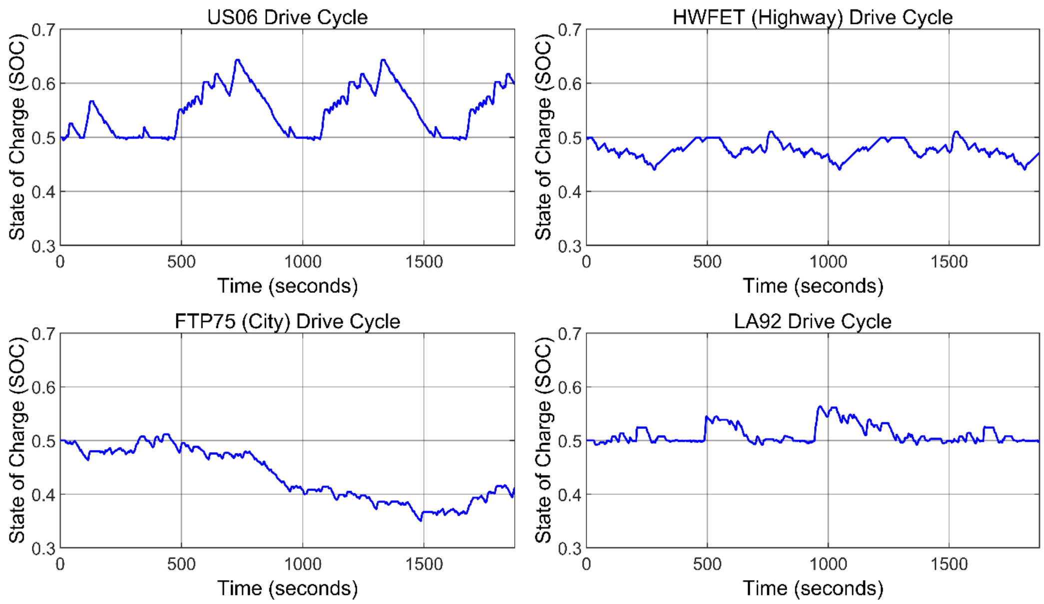



**Figure 11. Battery State of Charge versus Driving Time (1874 seconds)**

A summary of the energy values supplied and lost by different factors, total fuel used, miles traveled, averaged MPG, and SOC are shown in Table 2 for each driving cycle. Total Tractive Energy can be calculated by adding Total Energy Supplied by Engine, Total Energy Supplied by ESS, and Energy Lost to the ESS. This serves to validate the results calculated.

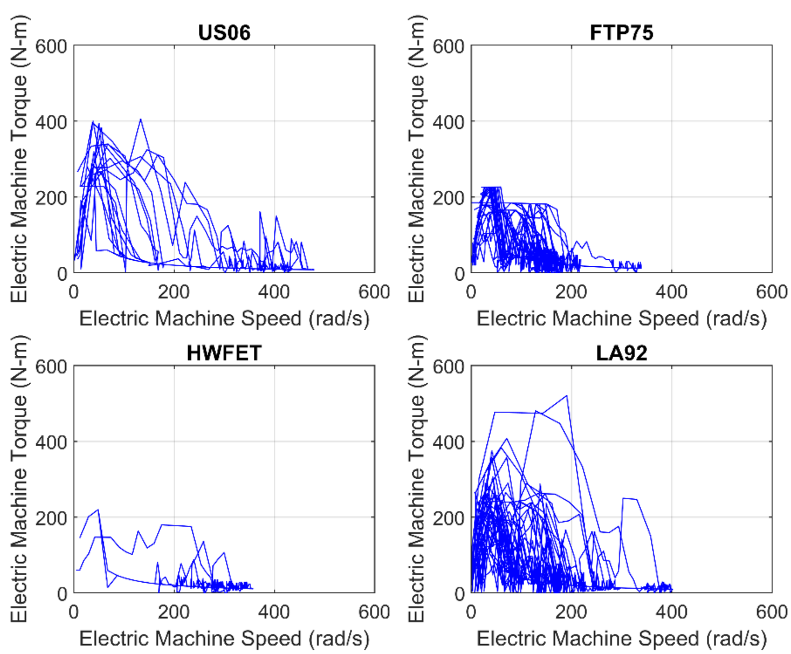



**Figure 12. Electric Machine Torque versus its RPM**

From Figure 12, it appears that for electric machine, the torque required is larger for lower RPM and it is smaller for larger RPM. For US06, the maximum torque appears to be 400 N-m at 100 rad/s. For FTP75, the maximum torque appears to be 200 N-m at 50 rad/s. for HWFET, the maximum torque appears to be constant around 200 N-m from 50-100 rad/s. for LA92, the maximum torque appears to be constant around 500 N-m at 200 rad/s.

**Table 2: Tabulated Results of Output Variables for Each Drive Cycle**

| Quantity | Units | (US06) | (FTP75) | (HWFET) | (LA92) |
|---|---|---|---|---|---|
| Total Tractive Energy | kWh | 7.098 | 2.067 | 5.488 | 2.902 |
| Total Energy Supplied by Engine | kWh | 8.192 | 2.417 | 6.046 | 3.513 |
| Total Energy Supplied by ESS | kWh | 1.508 | 1.013 | 1.119 | 1.090 |
| Energy Lost to the ESS | kWh | -2.602 | -1.363 | -1.677 | -1.702 |
| Energy Lost due to Drag | kWh | -3.456 | -0.523 | -2.267 | -0.877 |
| Energy Lost to Rolling Resistance | kWh | -2.998 | -1.349 | -3.005 | -1.532 |
| Total Fuel Used | Gal | 0.871 | 0.290 | 0.747 | 0.412 |
| Miles Traveled | Miles | 24.53 | 11.04 | 24.59 | 12.54 |
| Average Miles per Gallon | MPG | 27.08 | 37.59 | 31.93 | 29.61 |
| State of Charge (SOC) at the end | - | 0.598 | 0.412 | 0.471 | 0.50 |

In addition, we want to calculate the Tractive Power and MPG when the speed is 60mph. This is shown in Table 3. Using the Simulink model, we can calculate these values easily. My hand calculations using a calculator also validated the results. The accelerating forces are 0N, so the only forces acting are drag and rolling resistance forces.

**Table 3: At Steady Speed of 60 MPH**

| Variables | Using Calculator | Using Simulink |
|---|---|---|
| Tractive Power | 15,316 W | 15,315 W |
| Corresponding miles per gallon | 29.05 mpg | 29.07 mpg |

How much of tractive power is attributed to rolling resistance? As mentioned above, the only forces acting at a constant velocity are the rolling resistance and aerodynamic drag force. The percentage of Rolling Resistance Force is 48%. How much of tractive power is attributed to aerodynamic drag? The percentage of aerodynamic drag force is 52%.

**BONUS:**

**1. How does the round-trip efficiency of the ESS effect MPG?**

Here, I used FTP75 driving cycle for studying how round-trip efficiency of the ESS affects MPG values. From Table 4, round-trip efficiency does not seem to affect MPG very much. Round-trip efficiencies between 0.80-1.00 seem to increase MPG of the vehicle.

However, when round-trip efficiencies are less than 0.80, it does not seem to effect MPG. It could be due to SOC going to zero quickly when the round-trip efficiencies are less than 0.50. When SOC is 0, the ESS cannot help the drivetrain in Electric Launch Mode.

**Table 4: Round-trip Efficiency versus MPG**

| Round-Trip Efficiency ($\eta_{eff}$) | MPG |
|---|---|
| 0.2 | 37.24 |
| 0.4 | 37.24 |
| 0.6 | 37.24 |
| 0.8 | 37.63 |
| 1.0 | 43.50 |

**2. How does the storage capacity of the ESS effect MPG?**

MPG seems to reduce very slowly as energy storage of the ESS is increased. With high energy storage, the SOC does not fluctuate from 0.50.

**Table 5: ESS Energy Storage versus MPG**

| ESS Energy Storage (kWh) | MPG |
|---|---|
| 1 | 38.03 |
| 2 | 37.63 |
| 4 | 36.42 |
| 8 | 34.55 |
| 16 | 32.38 |

**3. How does the number of passengers or cargo weight effect MPG?**

As the number of passengers increase, the MPG seems to decrease. This is due to an increase in mass, which increases inertia, which increases the traction forces due to acceleration and deceleration of the vehicle. This could make the internal combustion engine burn more fuel.

**Table 6: Number of Passengers versus MPG**

| Number of Passengers | MPG |
|---|---|
| 1 | 37.63 |
| 2 | 35.92 |
| 3 | 34.21 |
| 4 | 33.36 |
| 5 | 32.64 |

4. **How does charge and discharge rate effect MPG?**
Increasing the charging rate decreases the miles per gallon calculated. This seems counterintuitive, but it could be due to the constant stop-go conditions of city driving, which consumes more energy.

**Table 7: Charge/Discharge Rate versus MPG**

| Charge/Discharge (kW) | MPG |
|---|---|
| 1 | 41.04 |
| 2 | 39.72 |
| 3 | 38.63 |
| 4 | 37.63 |
| 5 | 36.76 |

**Takeaways:** To improve the fuel efficiencies, it appears that increasing the round-trip efficiency of the ESS and decreasing the mass of the vehicle increases MPG.

## APPENDIX A: SIMULINK MODEL SETUP

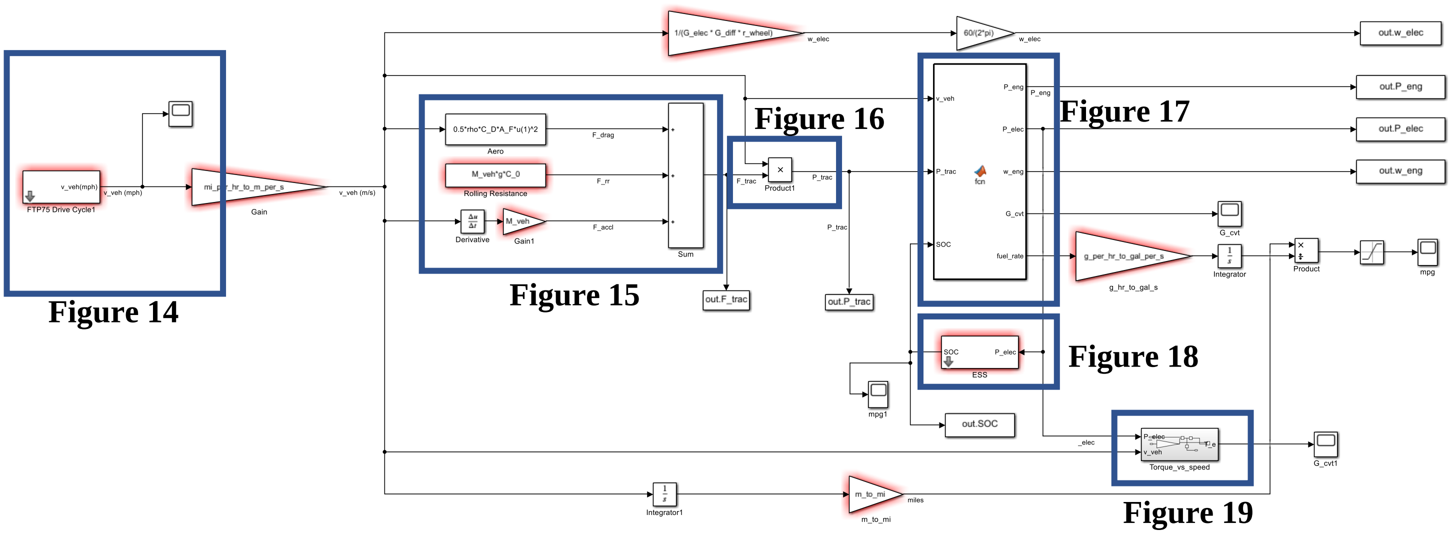



**Figure 13. Whole Simulink Block diagram**

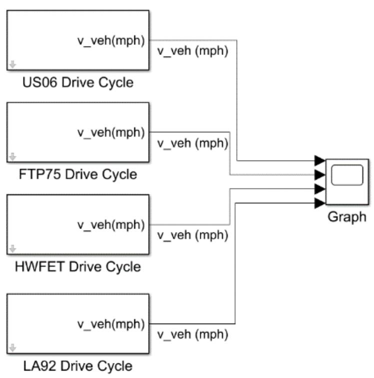



**Figure 14. Plotting all the driving cycles in one graph as shown in Figure 3**

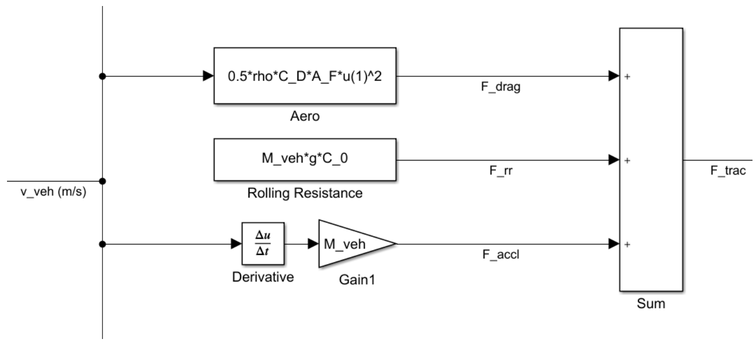



**Figure 15. Finding Traction Force from Aerodynamic drag, rolling resistance, and acceleration forces**

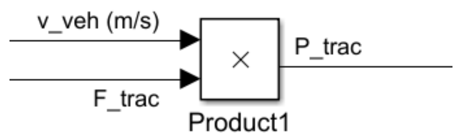



**Figure 16. Finding Traction Power in Simulink**

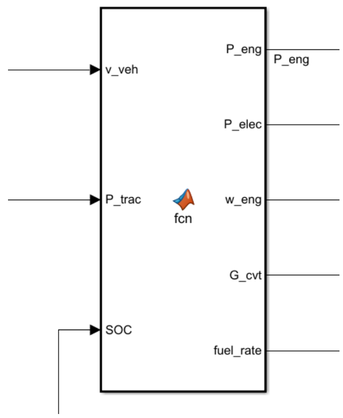



**Figure 17. This Simulink Block find all the output variables**

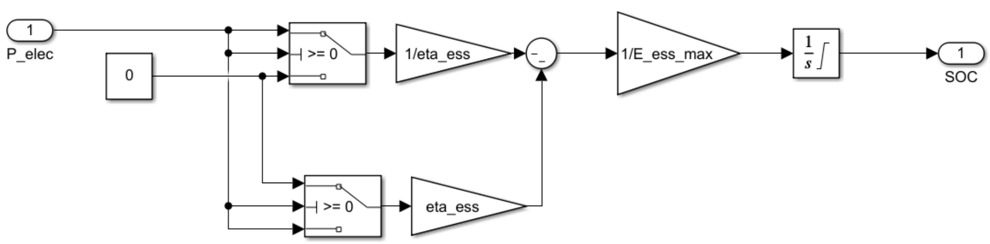



**Figure 18. Battery State of Charge Estimation in Simulink**

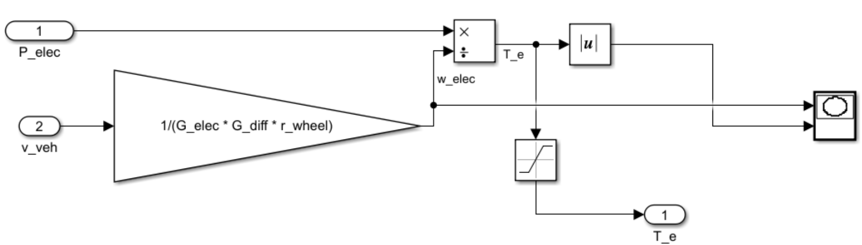



**Figure 19. Electric Motor Torque Estimation in Simulink**

## MATLAB CODE TEMPLATE FOR PLOTTING GRAPHS:

```
figure(1)
subplot(2,1,1)
plot(out.F_trac,'b')
ylabel("Tractive Force (N)")
title("Tractive Force versus Drive Time")
axis([0 axis_x_max -10000 10000])
grid on

subplot(2,1,2)
plot(out.P_trac, 'b')
xlabel("Time (seconds)")
ylabel("Tractive Power (W)")
title("Tractive Power versus Drive Time")
grid on
axis([0 axis_x_max -100000 150000])
```

## Initialization of all variables:

```
clear
M_glider = 1746;  % glider mass, kg
M_driver = 70; % driver mass kg
C_D = 0.35;    % drag coefficient
C_0 = 0.015;   % rolling resistance coefficient
A_F = 1.93;    % frontal area, m^2
eta_ess = 0.8; % energy storage subsystem round-trip efficiency
r_wheel = 0.2794; % wheel radius, m
P_eng_min = 10000.0; % min engine power, W
P_eng_max = 85000.0; % max engine power, W
G_diff = 0.268;     % differential gear ratio
G_cvt_min = 0.5;  % minimum tansmission gear ratio
w_eng_min = 1000; % minimum engine speed, rpm
E_batt = 2;   % battery capacity, kWh
SOC_init = 0.5; % initial SOC
m_batt = 21.74; % battery mass, kg/kw-hr
G_elec = 1; % gear ratio for motor

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

% unit conversions
m_to_mi = 1/1609; % meters to miles
g_per_hr_to_gal_per_s = 9.778e-8;  % g/hr to gal/s
mi_per_hr_to_m_per_s = 0.44704; % mi/hr to m/s

% calculated constants

v_veh_min = G_cvt_min * G_diff*r_wheel * w_eng_min * 2 * pi / 60;  % smallest vehicle speed
for engine to stay engaged, in m/s
E_ess_max = E_batt * 1000 * 3600; % energy storage capacity, J
M_batt = m_batt* E_batt;
M_veh = M_glider + M_driver + M_batt;

% load drive cycles
load hwfet.txt
load ftp75.txt
load us06.txt
load eng_map.txt
load la92.txt

% wrap parameters into structure
param.v_veh_min = v_veh_min ;
param.P_eng_min = P_eng_min ;
param.P_eng_max = P_eng_max ;
param.G_cvt_min = G_cvt_min ;
param.G_diff = G_diff ;
param.r_wheel = r_wheel ;
```

## Scripting Function:

```
function [P_eng, P_elec, w_eng, G_cvt, fuel_rate] = fcn(v_veh, P_trac, SOC, param, eng_map)
%#codegen
%inputs:
    % v_veh, m/s
    % P_trac, W
    % SOC
    % param, structure of parameters
    % eng_map

% outputs:
    %   P_gen, P_elec in W
    %   w_eng, rpm
    %   G_cvt (cvt ratio)
    %   Fuel rate, g/hr

v_veh_min = param.v_veh_min;    % minimum vehicle speed for engine to stay engaged, in m/s
P_eng_min = param.P_eng_min;    % minimum engine power in W
P_eng_max = param.P_eng_max ;   % maximum engine power
G_cvt_min = param.G_cvt_min;    % minimum cvt  ratio
G_diff = param.G_diff;          % differential gear ratio
r_wheel = param.r_wheel;        % wheel radius in m

if (v_veh < v_veh_min)  % disengage clutch, idle, engine, electric launch
   P_elec = P_trac;
   P_eng = 0;
   fuel_rate = 0; % g/hr;
   w_eng = 0; % rpm
   G_cvt = G_cvt_min;
   return
end

% if here, v_veh > v_veh_min
if(P_trac < P_eng_min)   % clutch engaged but no fuel
   P_elec = P_trac;
   fuel_rate = 0;
   P_eng = 0;
   w_eng =  1000; % rpm
   w_eng_SI = w_eng * 2 * pi / 60; % rad/s
   % set G_cvt so engine speed is 1000 rpm
   G_cvt = v_veh/G_diff/w_eng_SI/r_wheel;
   return
end

if(P_trac > P_eng_max) % high-speed boost
   P_elec = P_trac - P_eng_max;
   P_eng = P_eng_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_eng_SI = w_eng * 2 * pi / 60; % convert to rad/s
   G_cvt =  v_veh/r_wheel/G_diff/w_eng_SI; % required CVT ratio
   return
end

% if here, v_veh > v_veh_min and P_eng_min < P_trac < P_eng_max
% try to get SOC back to 0.5

P_elec = 5000*sign(SOC - 0.5);
P_eng = P_trac - P_elec;

if(P_eng < P_eng_min)
   % clutch engaged, but no fuel
   P_eng = 0;
   P_elec = P_trac;
   fuel_rate = 0;
   w_eng = 1000;
   w_eng_SI = w_eng * 2 * pi / 60; % om rad/s
   % set G_cvt so engine speed is 1000 rpm
   G_cvt = v_veh/G_diff/w_eng_SI/r_wheel;
   return
end

if(P_eng > P_eng_max)
    P_eng = P_eng_max;
    P_elec = P_trac - P_eng_max;
end

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_eng_SI = w_eng* pi / 30;  % convert to rad/s
G_cvt =  v_veh/r_wheel/G_diff/w_eng_SI;

if (G_cvt < G_cvt_min) % set G_cvt = G_cvt_min, recalculate w_eng, P_eng, and P_elec
   G_cvt = G_cvt_min;
   w_eng_SI = v_veh/G_diff/r_wheel/G_cvt;
   w_eng = w_eng_SI*30/pi;  % in rpm
   P_eng = 1000*interp1(eng_map(:,1), eng_map(:,2), w_eng) % in W
   P_elec = P_trac - P_eng;
   bsfc = interp1(eng_map(:,1), eng_map(:,3), w_eng);
   fuel_rate = bsfc*P_eng/1000; % g/hr
 end
```

## REFERENCES

[1] Wasynczuk, Oleg,. "Introduction to Architectures," *ECE 51018: Hybrid Electric Vehicles*, Accessed: February 19, 2021