ME 597 Project 1 Report

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Analysis of Parallel Hybrid Electric Vehicles

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1. Introduction

In parallel hybrid gas/electric vehicles, an electric machine is used to propel the vehicle at low speeds with the main engine disengaged. The electric machine also boosts the motor to improve acceleration, permitting a smaller internal combustion engine to be used. This report analyzes a parallel hybrid electric vehicle using Simulink and MATLAB. This includes evaluating the vehicle's performance in various driving cycles, focusing on power distribution, energy consumption, and efficiency. The simulation provides insight into fuel economy, battery state of charge variations, and overall drivetrain performance.

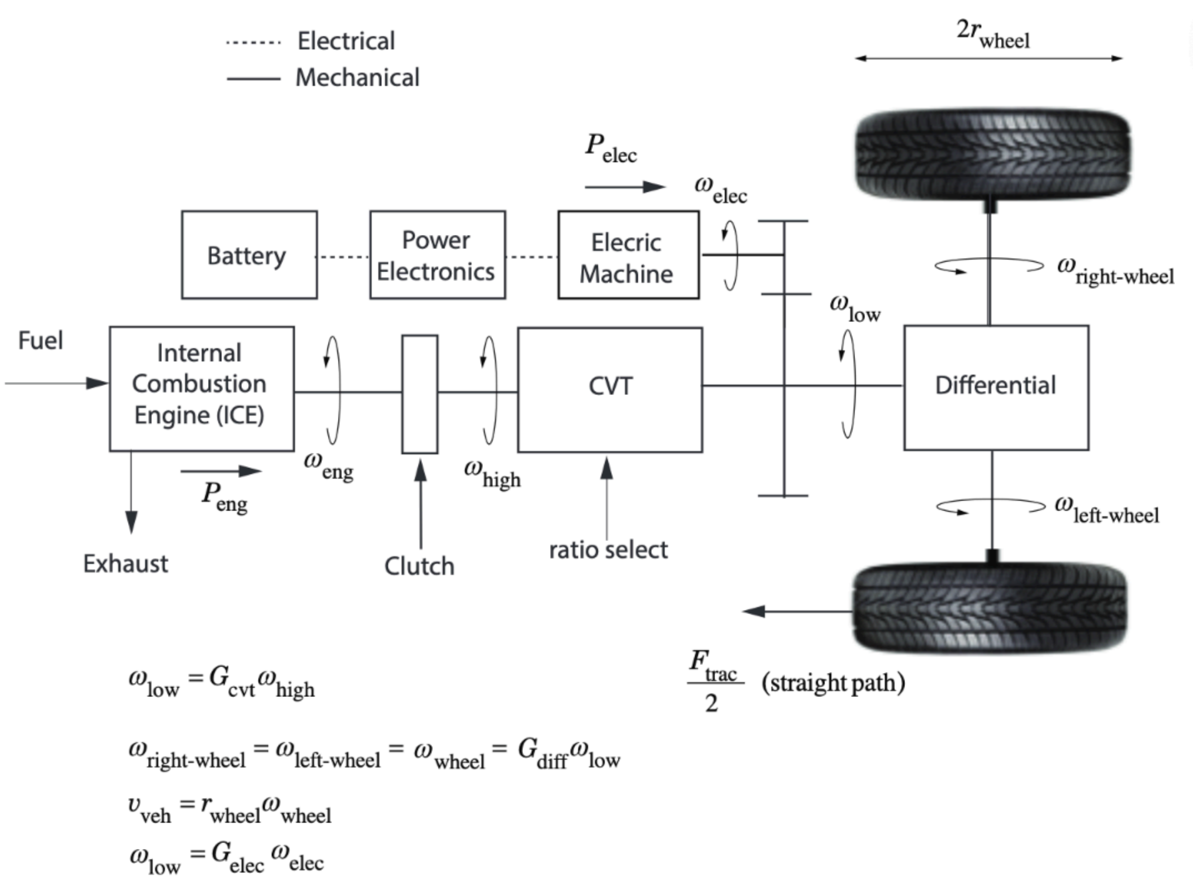


Figure 1: Parallel Hybrid Vehicle

2. Vehicle Model Description

The parallel hybrid vehicle consists of an internal combustion engine and an electric machine working together to optimize fuel efficiency and performance. Key vehicle parameters include the powertrain architecture, energy management strategy, and battery/energy storage. The powertrain architecture is a combination of the ICE and an electric motor. The energy management prioritizes using the electric motor at lower speeds and engine power at higher speeds. Lastly, the energy storage aims to maintain a battery state of charge between 0.2 and 0.8 with a target of 0.5.

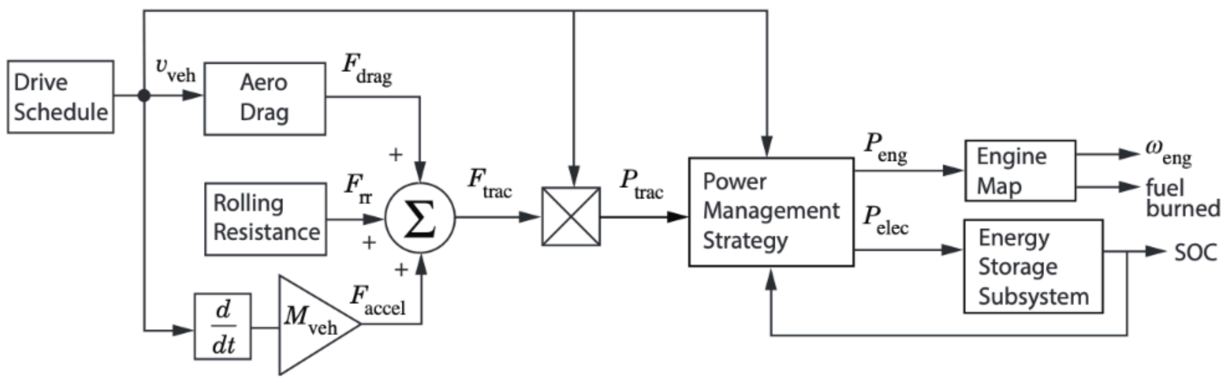


Figure 2: Top Level Block Diagram

3. Simulation Setup

The simulation model was developed in Simulink, using three different drive cycles. There are drive cycles to emulate city driving (UDDS), highway driving (HWFET), and aggressive driving (US06). The model also included a MATLAB function box that used the velocity of the vehicle, the tractive power, and the state of charge to determine a number of parameters. The full simulink model can be seen in Figure 3.

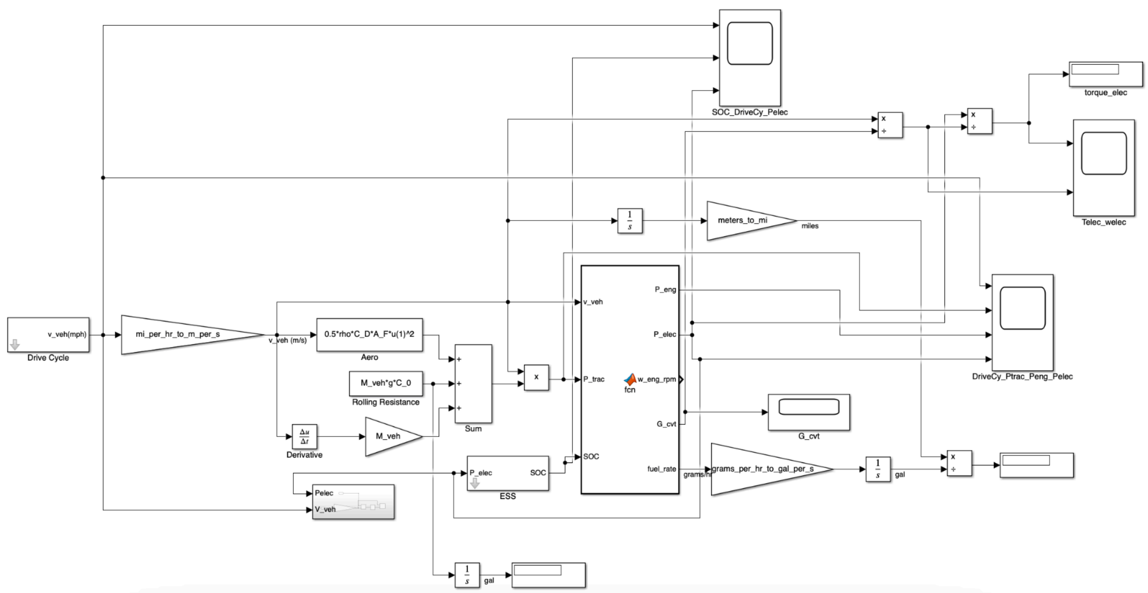


Figure 3: Simulink Model

4. Results & Discussion

4.1 Vehicle Performance Plots

The following plots illustrate key performance parameters for the “US06’ drive cycle:

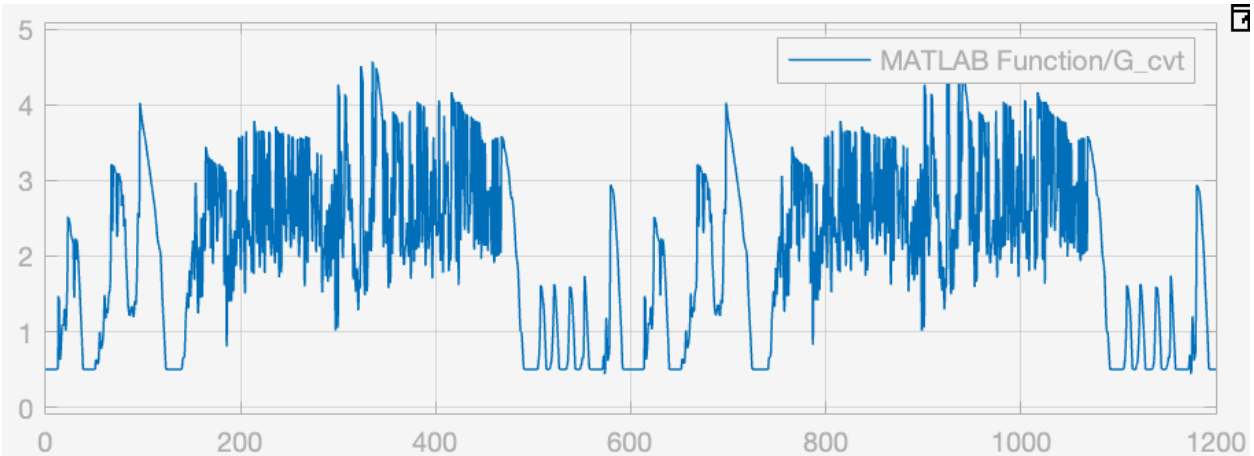


Figure 4: US06 CVT vs time

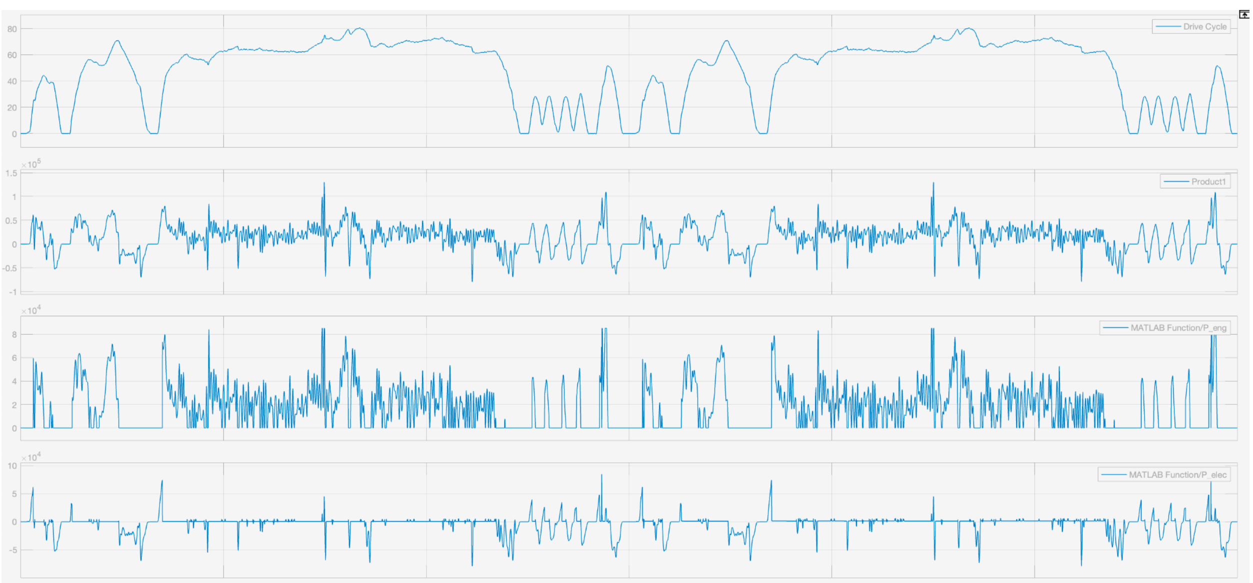


Figure 5: US06 Drive Cycle, P_trac, P_eng, P_elec vs time

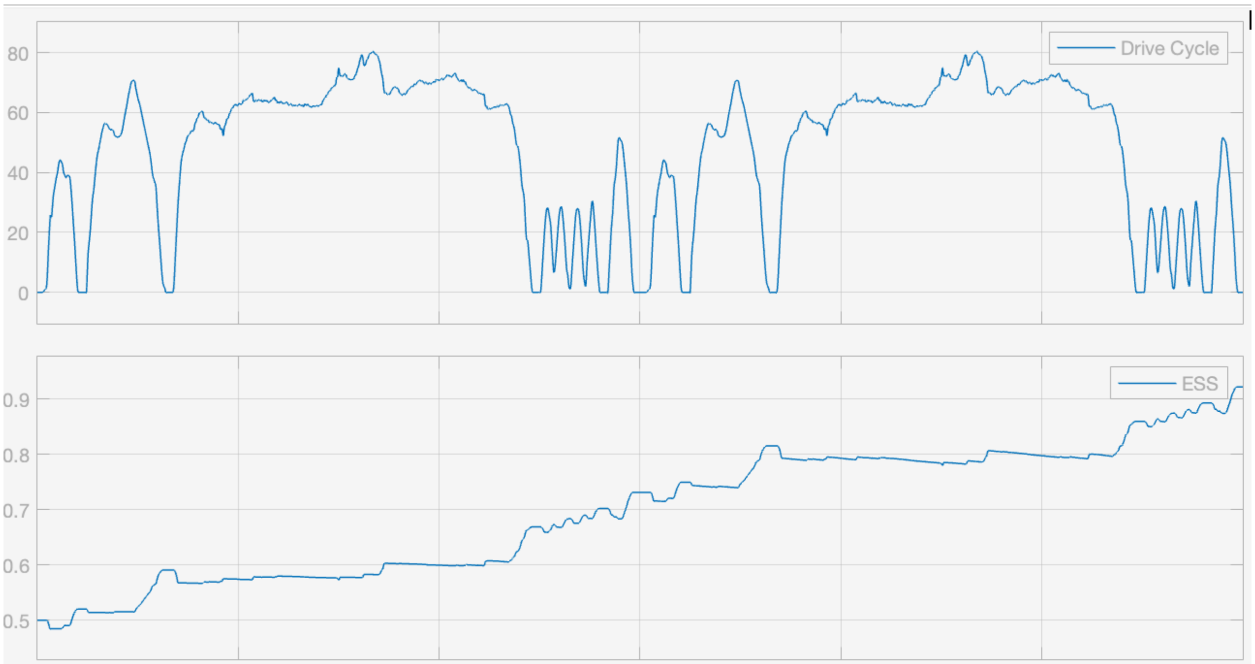


Figure 6: US06 ESS vs time

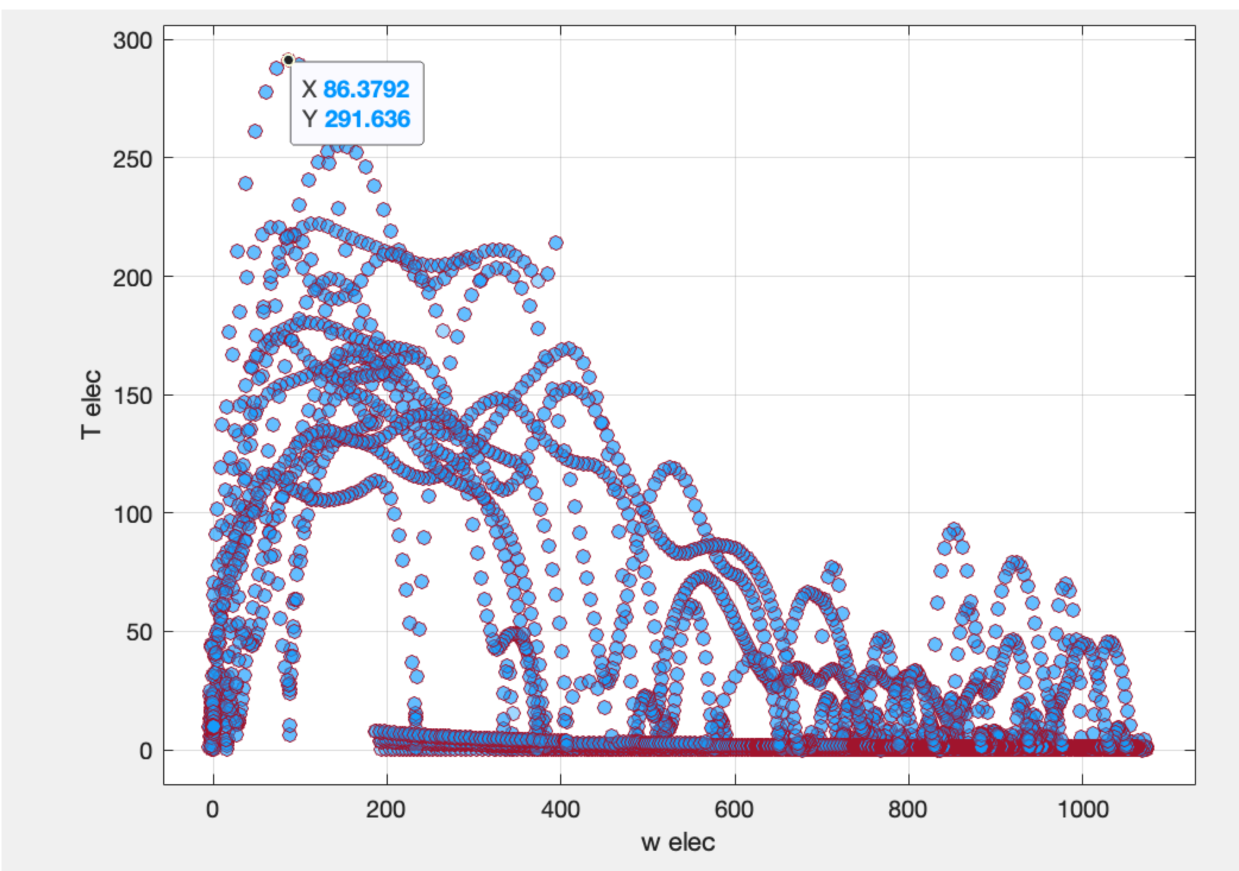


Figure 7: US06 T_elec vs w_elec

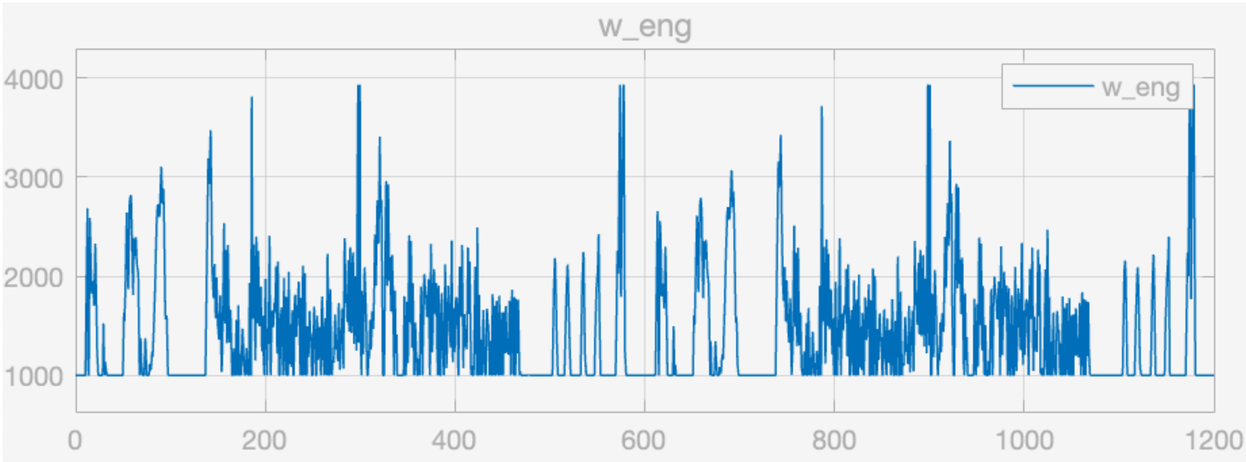


Figure 8: US06 w_eng_rpm vs time

The following plots illustrate key performance parameters for the “UDDS” drive cycle:

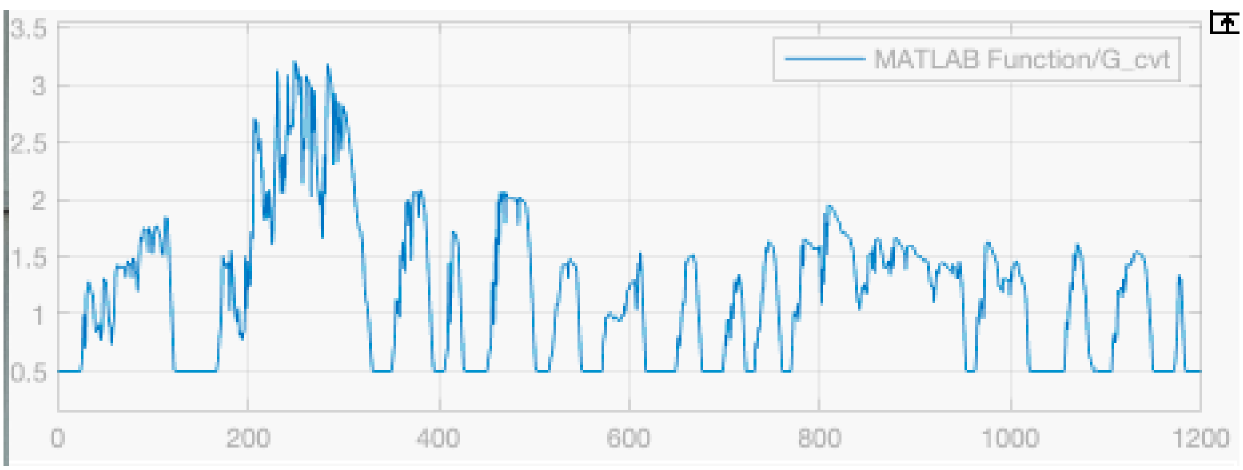


Figure 9: UDDS CVT vs time

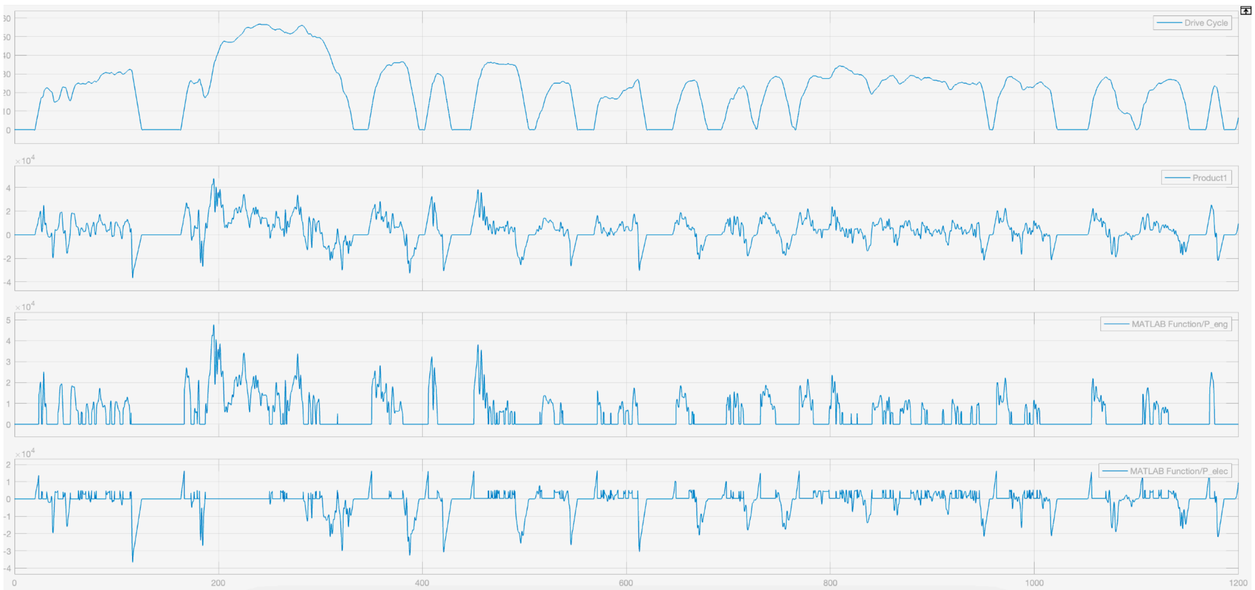


Figure 10: UDDS Drive Cycle, P_trac, P_eng, P_elec vs time

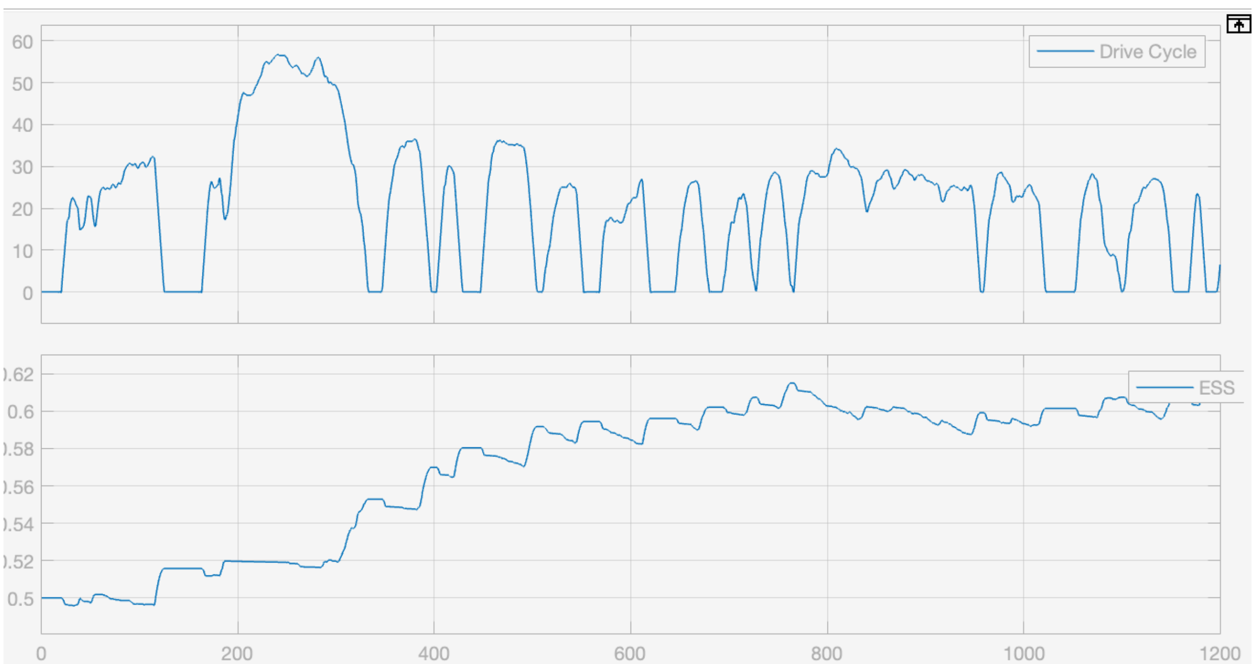


Figure 11: UDDS ESS vs time

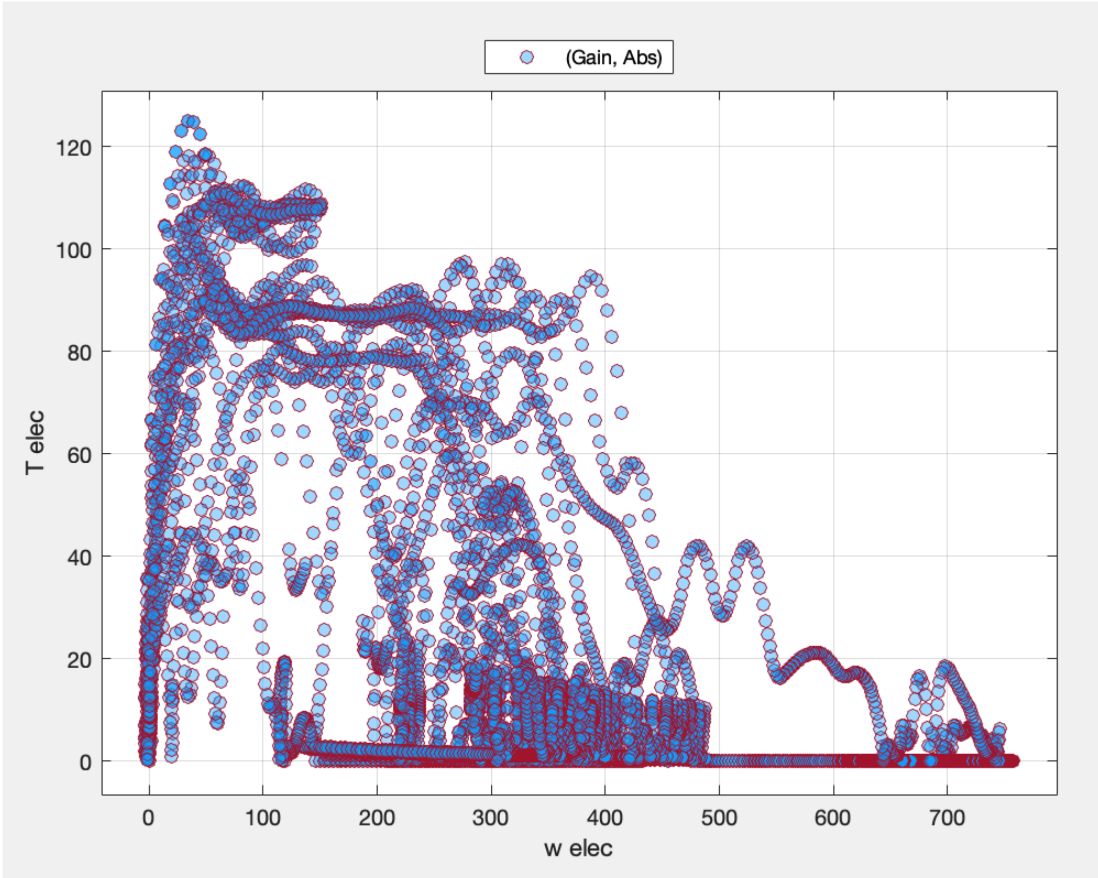


Figure 12: UDDS T_elec vs w_elec

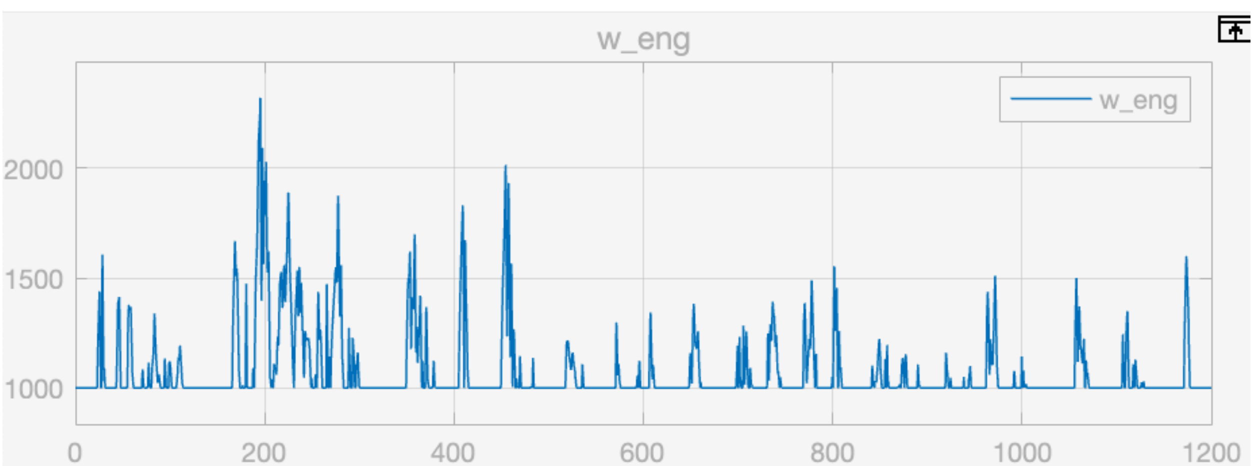


Figure 13: UDDS w_eng_rpm vs time

The following plots illustrate key performance parameters for the “HWFET” drive cycle:

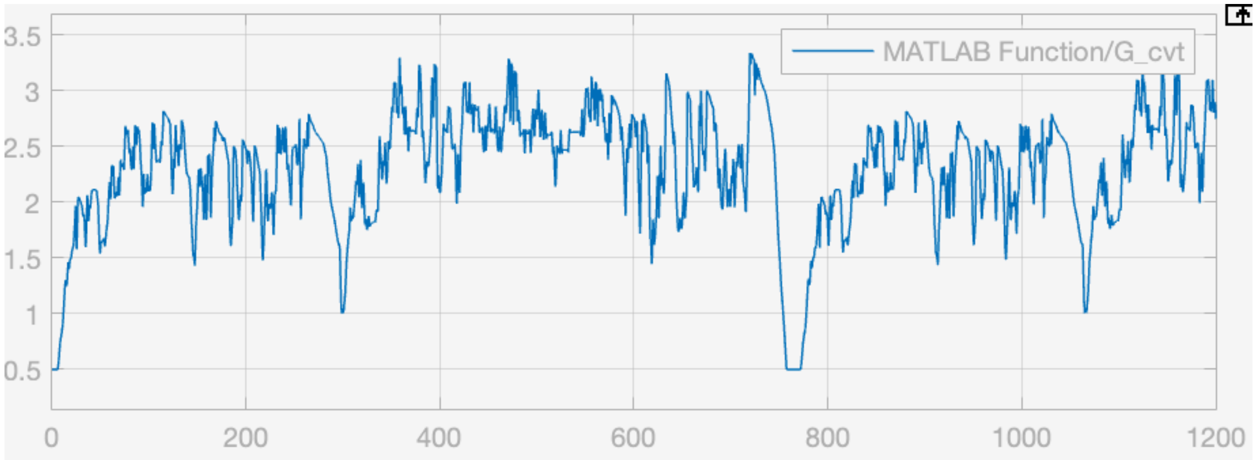


Figure 14: HWFET CVT vs time

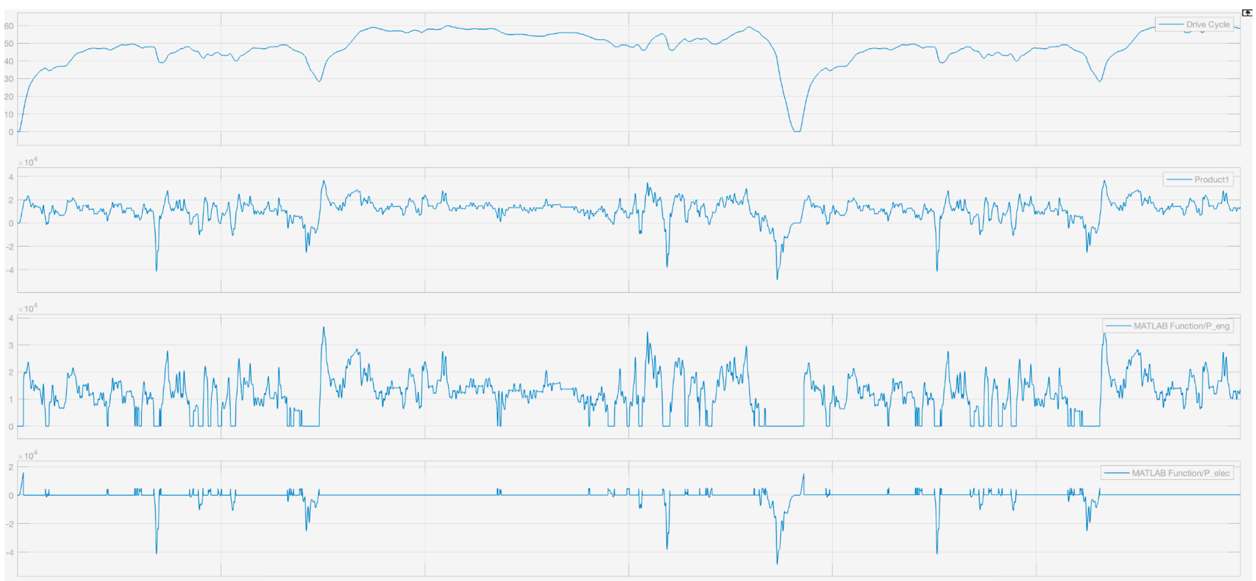


Figure 15: HWFET Drive Cycle, P_trac, P_eng, P_elec vs time

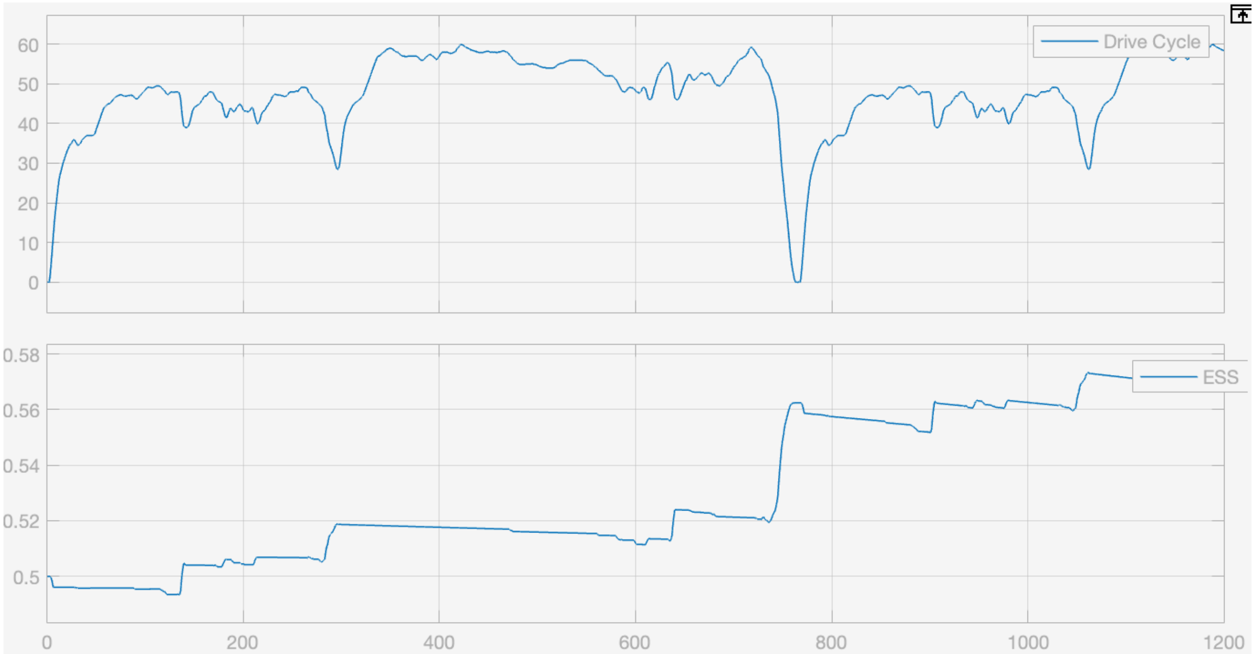


Figure 16: HWFET ESS vs time

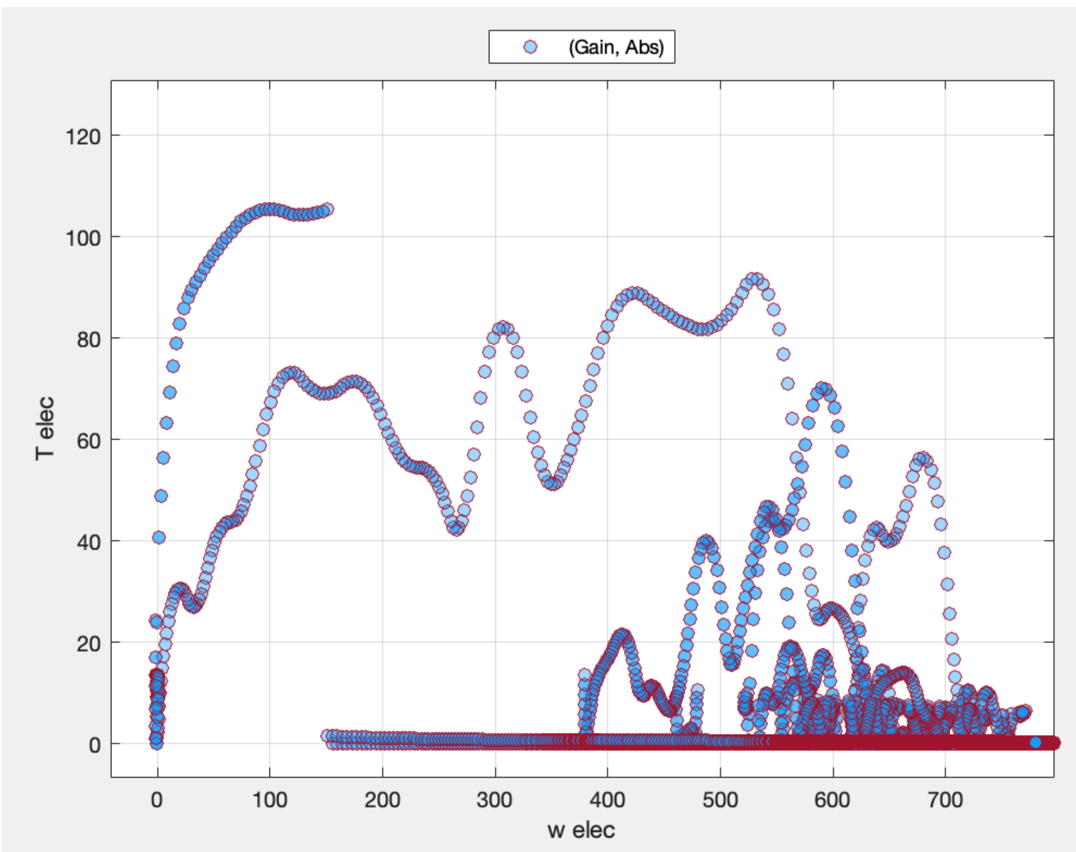


Figure 17: HWFET T_elec vs w_elec

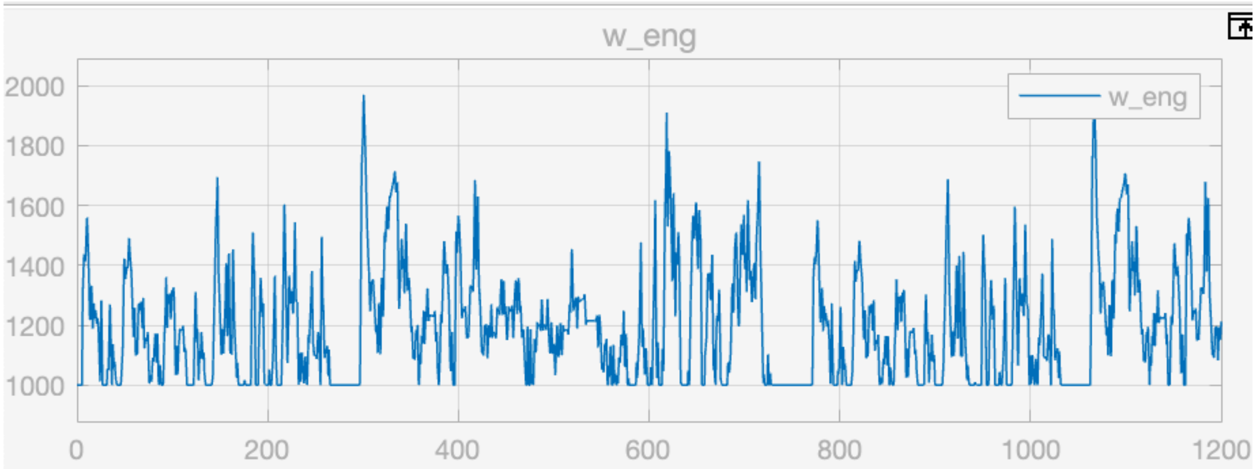


Figure 18: HWFET w_eng_rpm vs time

4.2 Energy Analysis

The energy contributions and losses were computed for each drive cycle. Energy analysis calculations can be seen in Appendix E.

Parameter	UDDS	HWFET	US06
Tractive Energy (kWh)	2.632	4.407	4.395
Engine Energy Supplied (kWh)	3.080	4.499	5.276
Motor Energy Supplied (kWh)	-0.449	-0.0924	-0.880
Energy Lost to Drag (kWh)	0.606	2.444	2.281
Energy Lost to Rolling Resistance (kWh)	1.962	1.794	2.081
Acceleration Energy Loss (kWh)	0.063	0.169	0.0329

Table 1: Energy Contributions per Two Drive Cycles

4.3 Fuel Economy Analysis

Fuel efficiency and overall vehicle economy were analyzed based on fuel consumption and mileage:

Parameter	UDDS	HWFET	US06
Total Fuel Used (gallons)	0.215	0.529	0.596
Distance Traveled (miles)	6.838	15.81	16.02
Average Fuel Economy (mpg)	31.83	29.9	26.86

Table 2: Fuel Efficiency per Drive Cycle

4.4 Discussion of Results

The US06 drive cycle represents the vehicle parameters through the perspective of aggressive driving. The first thing to note is the electric power consumption, which can be seen in Figure 5. When the power is negative, this indicates that the electric motor is acting as a generator and is actively charging the battery. This typically happens as the car goes downhill or is slowing down. This is key to the function of parallel hybrid vehicles that do not rely on plug in wall chargers for energy. Ideally, the battery state of charge should remain below 0.8, but for the aggressive driving cycle seen in Figure 6, the state of charge actually ends at a value exceeding 0.9. This could be a small issue with the MATLAB script and could be credited to the fact that with aggressive driving comes higher rates of extreme regenerative braking. Therefore, the battery is likely to stay charged better than on the highway. Outside of these abnormalities, the plots appear as expected. For example, while tractive power is high, the electric power and engine power are high as well to accommodate increased losses from drag force and rolling resistance. Lastly, it is important to note that the aggressive drive cycle yielded the least efficient gas mileage at 26.866 miles per gallon.

The UDDS drive cycle represents the vehicle parameters through the perspective of city driving. City driving typically entails stop and go traffic which means the expected mileage is worse in the city for cars with traditional internal combustion engines. However, in the case of the parallel hybrid vehicle, the electric motor aids to propel the car, especially at low speeds. Due to this characteristic, the urban drive cycle actually provides the best fuel economy at 31.83 miles per gallon, even better than the highway drive cycle. The battery state of charge ends at approximately 0.61, which is within the target range. Something to note from the energy analysis is that very little energy is lost to aerodynamic drag due to the low travel speeds, and the majority of energy loss comes from rolling resistance.

The HWFET drive cycle represents the vehicle parameters through the perspective of highway driving. Highway driving typically means the car is travelling at high speeds with little to no stopping or accelerating. Due to this, traditional internal combustion engine cars are expected to have better fuel efficiency under these conditions. In the case of this simulation, the highway drive cycle actually performs worse, with a gas mileage of 29.9 miles per gallon, almost 2 full miles less than city driving. This is credited towards an increased efficiency at lower speeds due to the electric motor. Also, the car experiences much greater energy loss due to drag at high speeds, while still experiencing similar rolling resistance energy loss. The battery state of charge ends around 0.58, which is less than the urban performance. This is probably due to less regenerative braking opportunities when maintaining a constant speed.

5. Appendix

Appendix A: Vehicle Parameters

Parameter	Symbol	Value
vehicle mass w/o battery, passengers, or driver	M_{veh}	1746 kg
driver and passenger mass	$M_{\text{passengers}}$	180 kg
wheel radius	r_{wheel}	0.2794 m
electric machine gear ratio	G_{elec}	1
transmission gear ratio (min)	$G_{\text{cvt,min}}$	0.5
transmission gear ratio (max)	$G_{\text{cvt,max}}$	TBD
differential gear ratio	G_{diff}	0.268
rolling resistance coefficient	C_0	0.015
aerodynamic drag coefficient	C_D	0.35
frontal area	A_F	1.93 m^2
initial energy storage subsystem capacity	E_{ess}	2 kWh
energy storage subsystem round-trip efficiency	η_{ess}	0.8
minimum engine speed	$\omega_{\text{eng,min}}$	1000 rpm
minimum engine power	$P_{\text{eng,min}}$	5 kW
maximum engine power	$P_{\text{eng,max}}$	85 kW
initial SOC	SOC_{init}	0.5
target SOC	$\text{SOC}_{\text{target}}$	0.5
maximum SOC	SOC_{max}	0.8
minimum SOC	SOC_{min}	0.2
mass density of gasoline	m_{gas}	0.75 kg/liter
mass density of ESS	m_{ess}	25 kg/kWh

Appendix B: MATLAB initialization script

```
clear all

M_glider = 1746;  % glider mass, kg

M_passengers = 180; % 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 = 5000.0; % min engine power, W

P_eng_max = 85000.0; % max engine power, W

G_diff = 0.268;     % differential gear ratio

w_eng_min_rpm = 1000; % minimum engine speed in rpm

E_batt_kW = 2.0;   % battery capacity, kW

SOC_init = 0.5; % initial SOC

m_batt = 25; % battery mass density, kg/kWh

G_elec = 1; % gear ratio for motor

G_cvt_min = 0.5;

% physical constants

rho = 1.225; % density of air, kg/m^3

g = 9.81; % acceleration due to gravity,  m/s^2

% unit conversions

meters_to_mi = 1/1609; % meters to miles
```

```
grams_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

w_eng_min = w_eng_min_rpm * 2 * pi / 60;

v_veh_min = G_cvt_min * G_diff * r_wheel * w_eng_min;  % smallest vehicle speed for engine to stay engaged, in m/s

E_ess_max = E_batt_kW * 1000 * 3600; % energy storage capacity in J

M_batt = m_batt* E_batt_kW; % battery mass in kg

M_veh = M_glider + M_passengers + M_batt;

% load drive cycles and engine map

load hwfet

load ftp75

load us06

load la92

load udds

load wltc

load eng_map

% wrap some parameters into structure "param"

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 ;
```

Appendix C: Simulink Function Block

```
function [P_eng, P_elec, w_eng_rpm, 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, rpm

   %   G_cvt (cvt ratio)

   %   Fuel rate, grams/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 propulsion

  P_elec = P_trac;
```

```
  P_eng = 0;

  fuel_rate = 0; % g/hr;

  w_eng_rpm = 1000; % rpm

  G_cvt = G_cvt_min;

  return

end

% if here, v_veh > v_veh_min

if(P_trac < P_eng_min)   % clutch engaged but engine idling

  P_elec = P_trac;

  fuel_rate = 0;

  P_eng = 0;

  w_eng_rpm =  1000; % rpm

  w_eng = w_eng_rpm * pi / 30; % rad/s

  % set G_cvt so engine speed is 1000 rpm

  G_cvt = v_veh/G_diff/w_eng/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, 'pchip', 'extrap');

  fuel_rate = bsfc*P_eng/1000; % grams/hr

  w_eng_rpm = interp1(eng_map(:,2), eng_map(:,1), P_eng/1000, 'pchip', 'extrap');
```

```
  w_eng = w_eng_rpm * pi / 30; % convert to rad/s
  G_cvt =  v_veh/r_wheel/G_diff/w_eng; % 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 = 4000*(SOC - 0.5);
if(P_elec > 4000)
   P_elec = 4000;
end
if(P_elec < -4000)
   P_elec = -4000;
end
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_rpm = 1000;
  w_eng = w_eng_rpm * 2 * pi / 60; % in rad/s
  % set G_cvt so engine speed is 1000 rpm
  G_cvt = v_veh/G_diff/w_eng/r_wheel;
```

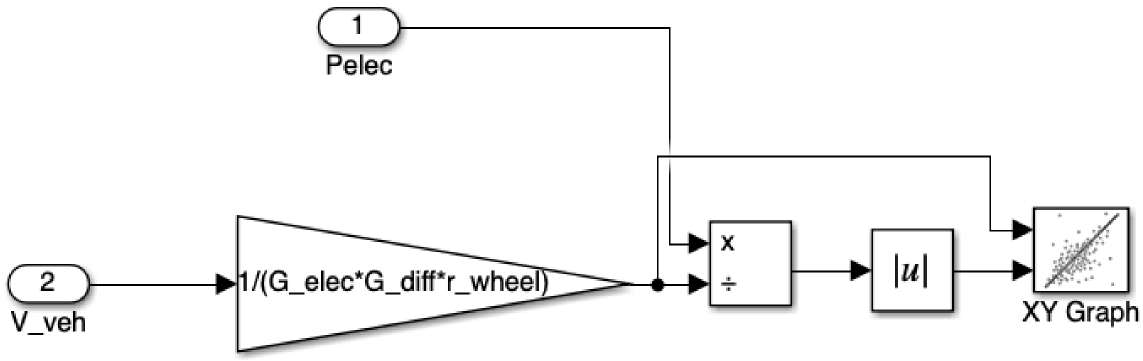
```
  return
end
if(P_eng > P_eng_max)
   P_eng = P_eng_max;
   P_elec = P_trac - P_eng_max;
end
bsfc = interp1(eng_map(:,2), eng_map(:,3), P_eng/1000, 'pchip', 'extrap');
fuel_rate = bsfc*P_eng/1000; % grams/hr
w_eng_rpm = interp1(eng_map(:,2), eng_map(:,1), P_eng/1000, 'pchip', 'extrap');
if(w_eng_rpm < 1000)
   w_eng_rpm = 1000;
end
w_eng = w_eng_rpm * pi / 30;  % convert to rad/s
G_cvt =  v_veh/r_wheel/G_diff/w_eng;
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 = v_veh/G_diff/r_wheel/G_cvt;
  w_eng_rpm = w_eng*30/pi;  % in rpm
  P_eng = 1000*interp1(eng_map(:,1), eng_map(:,2), w_eng, 'pchip', 'extrap'); % in W
  if(P_eng < 0)
     P_eng = 0;
  end
  P_elec = P_trac - P_eng;
```

```
  bsfc = interp1(eng_map(:,1), eng_map(:,3), w_eng, 'pchip', 'extrap');

  fuel_rate = bsfc*P_eng/1000; % grams/hr

end
```

Appendix D: Simulink Subsystem Screenshot



Appendix E: Energy Analysis

Total Energy Supplied = Motor Energy + Engine Energy

-0.449 + 3.080 = ~2.632 kWh

Total Energy Loss = Acceleration Energy Loss + Drag Loss + Rolling Resistance Loss

0.063 + 0.606 + 1.962 = ~2.632 kWh

The net energy supplied by the engine and ESS is equal to the sum of losses due to the first law of thermodynamics.