Analysis of a Parallel Hybrid Electric Vehicle

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Introduction

The goal of this project is to evaluate the performance of a hybrid gas/electric vehicle with parallel configuration. The electric machine in the vehicle serves as the primary means of propulsion at low speeds, while the main speed is disengaged. Furthermore, it functions as a booster motor, enhancing acceleration at high speeds. The diagram in Figure. 1 illustrates the drivetrain layout of the vehicle. The engine is designed to operate along the optimal BSFC curve, and a simplified energy storage subsystem model is utilized to achieve this. The energy storage subsystem has adequate capacity, ensuring that the state of charge (SOC) stays within the range of 0.2 to 0.8, with the aim of maintaining a target SOC of 0.5. A Simulink model is developed to analyze the architecture in Figure. 1 for three drive schedules published by US EPA. These drive schedules, which are taken as input by the Simulink model are UDDS(city), HWFET(highway) and US06 (aggressive highway). For each drive cycle, the total tractive energy, energy supplied by the engine, energy supplied by the ESS, energy lost to aerodynamic drag, the energy lost to ESS, the energy lost to rolling resistance are calculated. At the end of each drive cycle, the total fuel used, the miles travelled, average miles per gallon and the SOC are calculated. In addition, certain variables are plotted to analyze the performance of the vehicle. These variables are listed in Table 1.

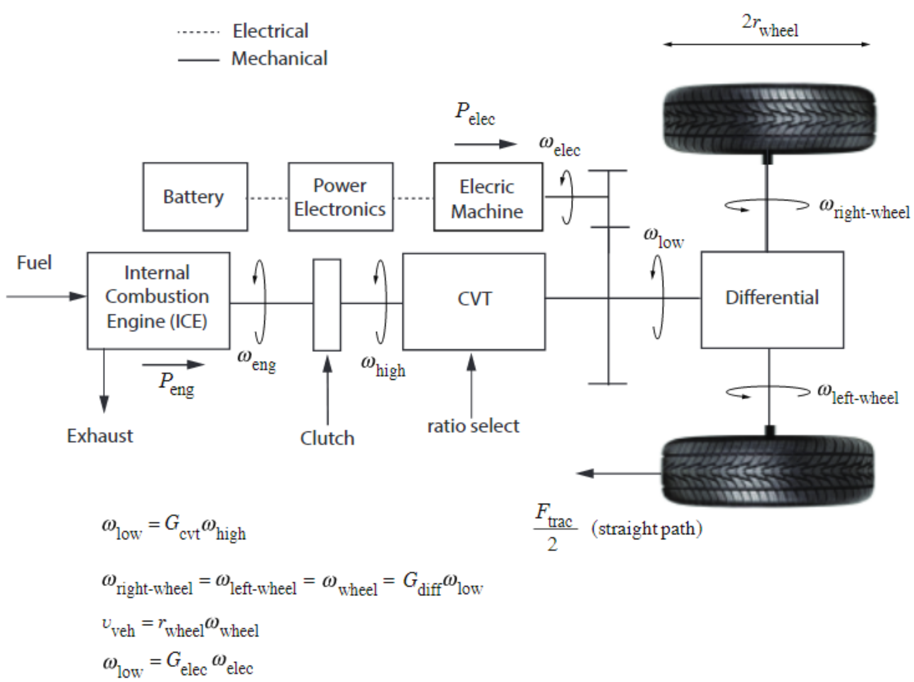


Figure 1 Parallel Hybrid Vehicle

Simulink Model and Physics

This section will go over the development of the Simulink model and some of its important blocks for the given vehicle architecture and the pertinent equations used to develop the model. The Simulink model is given below:

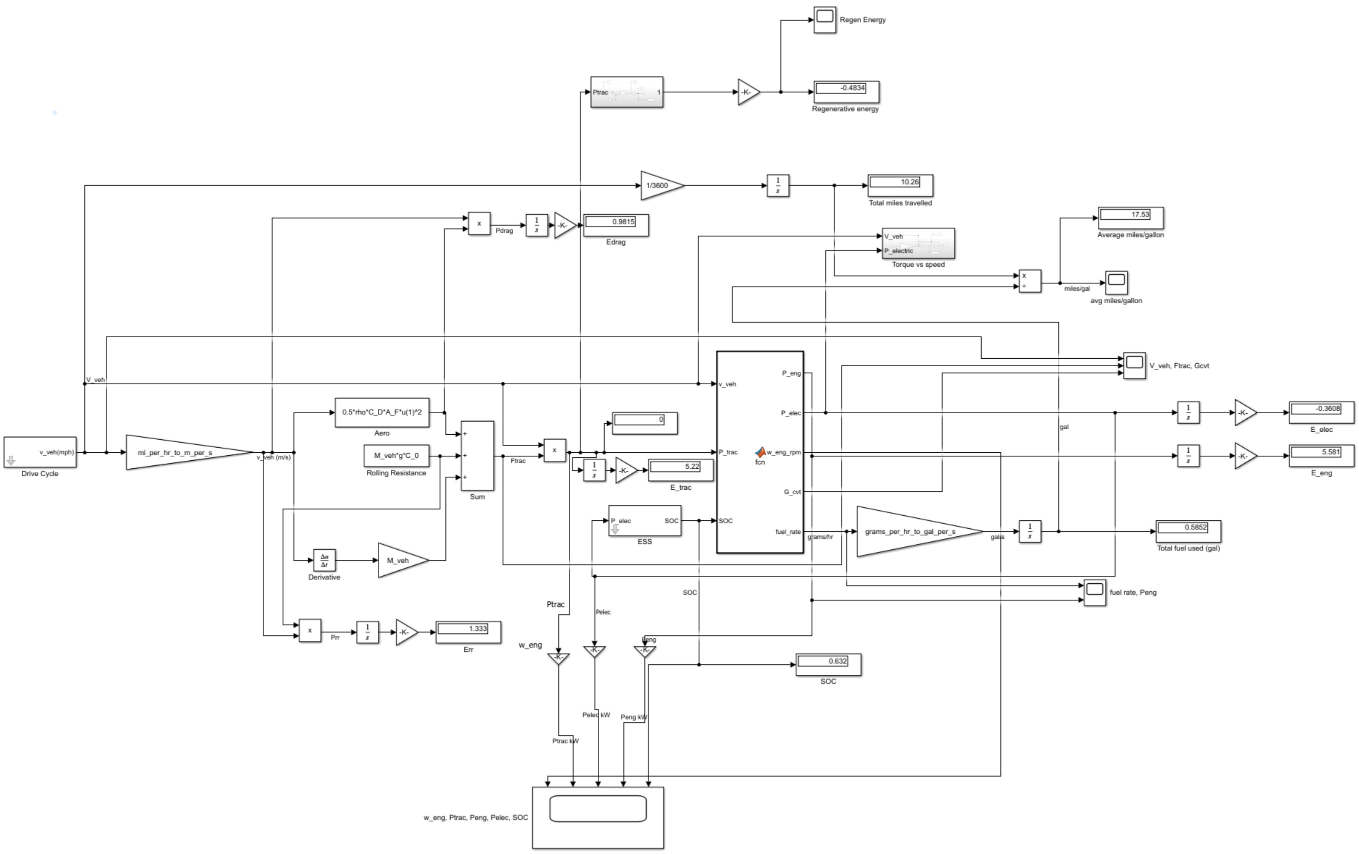


Figure 2 Simulink Model

The vehicle parameters is given in Table 1. The engine optimum speed and BSFC vs power Table is given in Table 2

Table 1 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

Table 2 Engine optimum speed and BSFC vs power

Power (kW)	Speed (rpm)	BSFC (g/kWh)
7.66423	1009.3	500
12.7737	1183.18	400
24.635	1588.89	320
35.7664	1936.6	285
47.6277	2318.13	265
57.2993	2612.71	255
77.7372	3371.09	255
82.8467	3685.23	265
85.5839	4014.0	285

In this model, the tractive force is opposed by the force due to aerodynamic drag and rolling resistance. There is no grade force in the system. Therefore, the net road load force can be defined by:

$$F_{RL} = F_{RR} + F_{AD}$$

Here, F_{RL} = Road Load force,
F_{RR} = Rolling resistance = Mveh*g*C0
F_{AD} = Aerodynamic drag force = $0.5 * \rho * C_D * A_F * V_{veh}$
Applying Newton's second law,

$$\sum_i Fi = ma$$

$$F_{TE} - F_{RL} = ma$$

$$F_{TE} = ma + F_{RL}$$

$$\boxed{F_{TE} = ma + F_{RR} + F_{AD}}$$

This relation is drawn in Simulink as shown by Figure 3. To find the P_{trac} which is the total tractive power, F_{trac} is multiplied by the vehicle velocity.

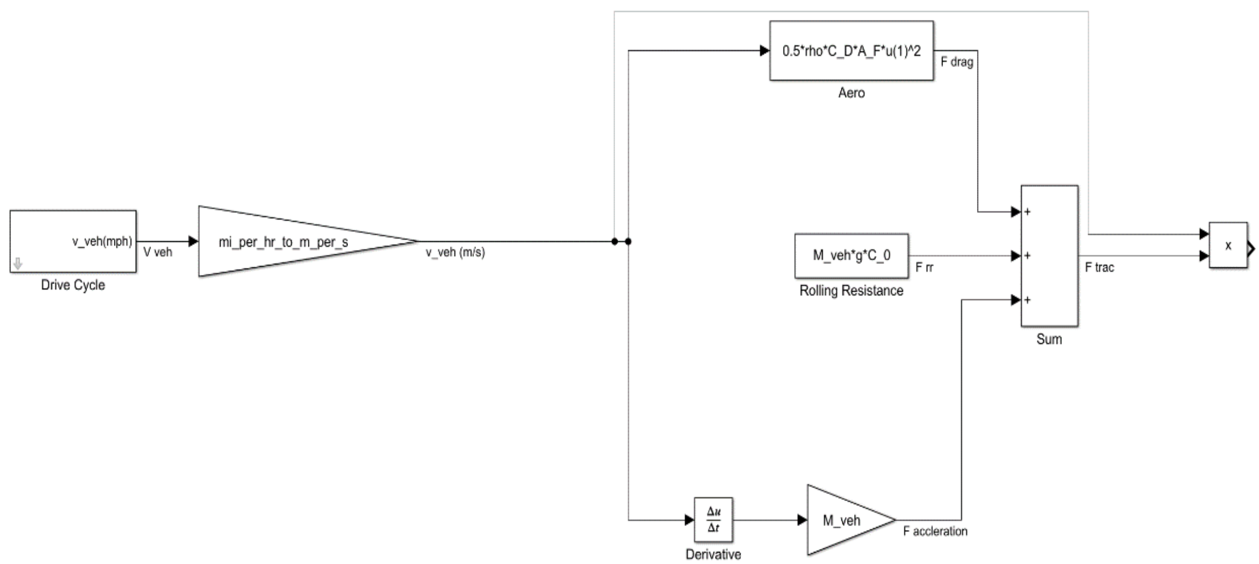


Figure 3 Calculating Tractive power in Simulink

Function Block

Next, a function block is created which takes in the velocity of the vehicle, the tractive power and SOC as inputs and calculates the power supplied by the engine, the power supplied by the ESS, ωeng, fuel rate and gear ratio for the cvt. The MATLAB code behind the function block is given in the Appendix 2

Inside the function block, the power management strategy is defined. Given the required net tractive power P_{trac}, the power manager determines how much of the required power is to be supplied by the engine. The difference is to be supplied or absorbed by the energy storage subsystem. The strategy is to maintain an average SOC of 0.5. That is, the ESS is used to provide boost power only in times needed. Other constraints are defined as follows:

1. If the vehicle speed is below a threshold, the clutch is disengaged, and the engine is idling. The vehicle-speed threshold occurs when the CVT is operating at its lowest gear ratio $G_{cvt,min}$ and $\omega_{eng} = \omega_{eng,min}$. In this mode of operation, $P_{eng} = 0$ and $P_{trac} = P_{elec}$. This is called electric launch mode. This is defined inside the function block as follows:

```
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
```

2. If $V_{veh} > V_{veh,min}$ and required P_{trac} is less than minimum engine power ($P_{eng,min}$), the clutch is engaged but no fuel is provided to engine ($P_{eng} = 0$). In this mode, $P_{elec} = P_{trac}$. A positive P_{trac} is supplied BY the electric machine (making it a motor) while a negative P_{trac} means that mechanical power is supplied TO the electric machine (making it a generator). The latter case is known as regenerative braking. The CVT ratio is controlled so that $\omega_{eng} = \omega_{eng,min}$. This is called all-electric mode. This is defined inside the function block as follows:

```
% 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
```

3. If P_{trac} is greater than maximum engine power along the optimum BSFC line (85 kW), assume $P_{eng} = P_{eng,max}$. $P_{eng,max}$ is initialized to 85 kW. In this mode, $P_{elec} = P_{trac} - P_{eng,max}$. This is called the electric boost mode.

```
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
```

4. Whenever $V_{veh} > V_{veh,min}$ and $P_{eng,min} < P_{trac} < P_{eng,max}$, we try bring the SOC back to 0.5 by charging or discharging the ESS. Initially, we use $P_{elec} = 20000\times\text{sign}(SOC-0.5)$ and $P_{eng} = P_{trac} - P_{elec}$. If the calculated P_{eng} falls below $P_{eng,min}$, the clutch remains engaged; however, fuel is shut off ($P_{eng} = 0$) In this case, the CVT ratio is controlled so that engine speed is $\omega_{eng,min}$. This is called the charge-sustaining mode.

```
% 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 = 20000*(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
```

Energy Storage Subsystem (ESS)

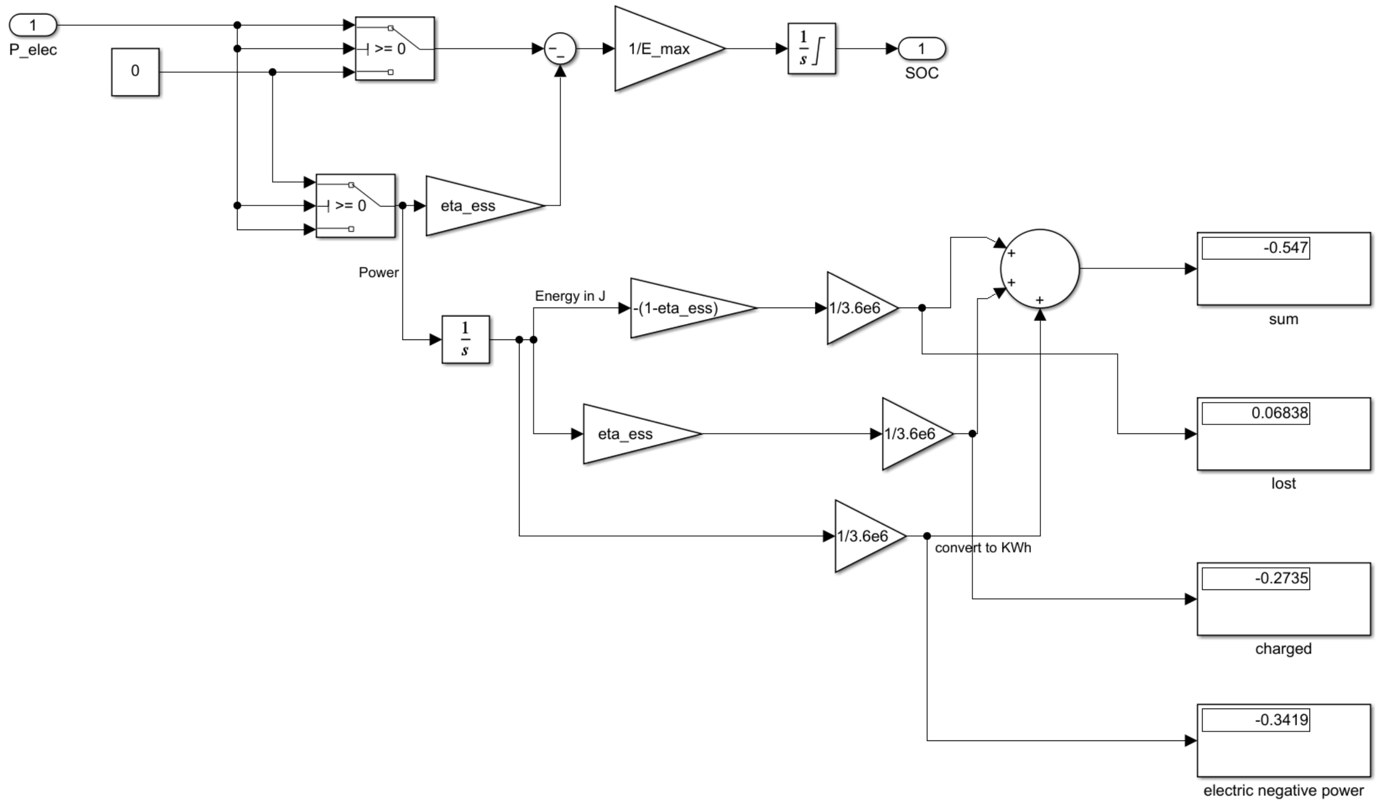


Figure 4 Energy Storage Subsystem

Above is the block diagram of the Energy Storage Subsystem. It takes P_{elec} as the input and calculates the SOC, the energy lost due to ESS, energy charged and the electric negative power.

Regenerative Power

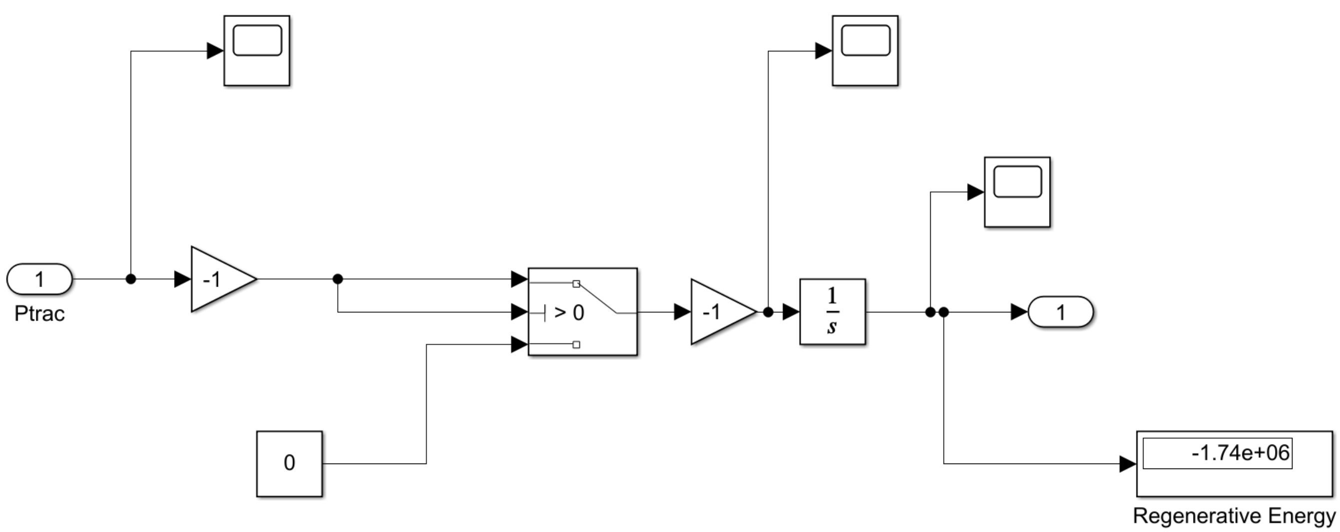


Figure 5 Regenerative power subsystem

A subsystem is created to calculate the regenerative power in a given drive cycle. Regenerative braking happens when we have a negative tractive power. Negative tractive power means that mechanical power is supplied to the electrical machine, making it a generator. In this model, we assume that the all of the negative tractive power is provided to the battery and there are no losses. In such a case, the sum of all the negative tractive power will give the regenerative power. In the above subsystem, a switch block is attached to output the negative tractive power from the total tractive power. This value is integrated over the entire duration of the drive cycle to get the regenerative energy.

Results

The results present an analysis of the tractive energy, engine and ESS energy supplied, as well as energy losses due to aerodynamic drag and rolling resistance for various drive cycles. The primary objective is to calculate the total tractive energy, energy supplied by the engine and ESS, and energy losses for each drive cycle, which is presented in the form of a table. The variables to be plotted is shown in Table 3

Additionally, this section includes the computation of the total fuel used, miles traveled, average miles per gallon, and the state of charge (SOC) at the end of the drive cycle. These results are presented in tabular format. It is important to note that to obtain a converged value for miles per gallon, the simulation stop time was set larger than the duration of one cycle to capture multiple cycles.

To verify the accuracy of the results, a first-law-of-thermodynamics check is conducted. The net energy supplied by the engine and ESS is expected to equal the sum of losses (aerodynamic and rolling resistance) plus the difference in kinetic energies at the end and start of the drive cycle.

Table 3 Variables to be plotted

Variable	Symbol	Unit
Engine speed	ω_{eng}	rpm
Engine power	P_{eng}	kW
Electric machine power	P_{elec}	kW
Electric machine speed	ω_{elec}	rpm
Electric machine torque	T_{elec}	N-m
Tractive force	F_{trac}	N
Tractive power	P_{trac}	kW
ESS state of charge	SOC	-

UDDS(city)

This drive cycle highlights the driving conditions in the city. For the simulation, the simulation time is set to 1369 seconds.

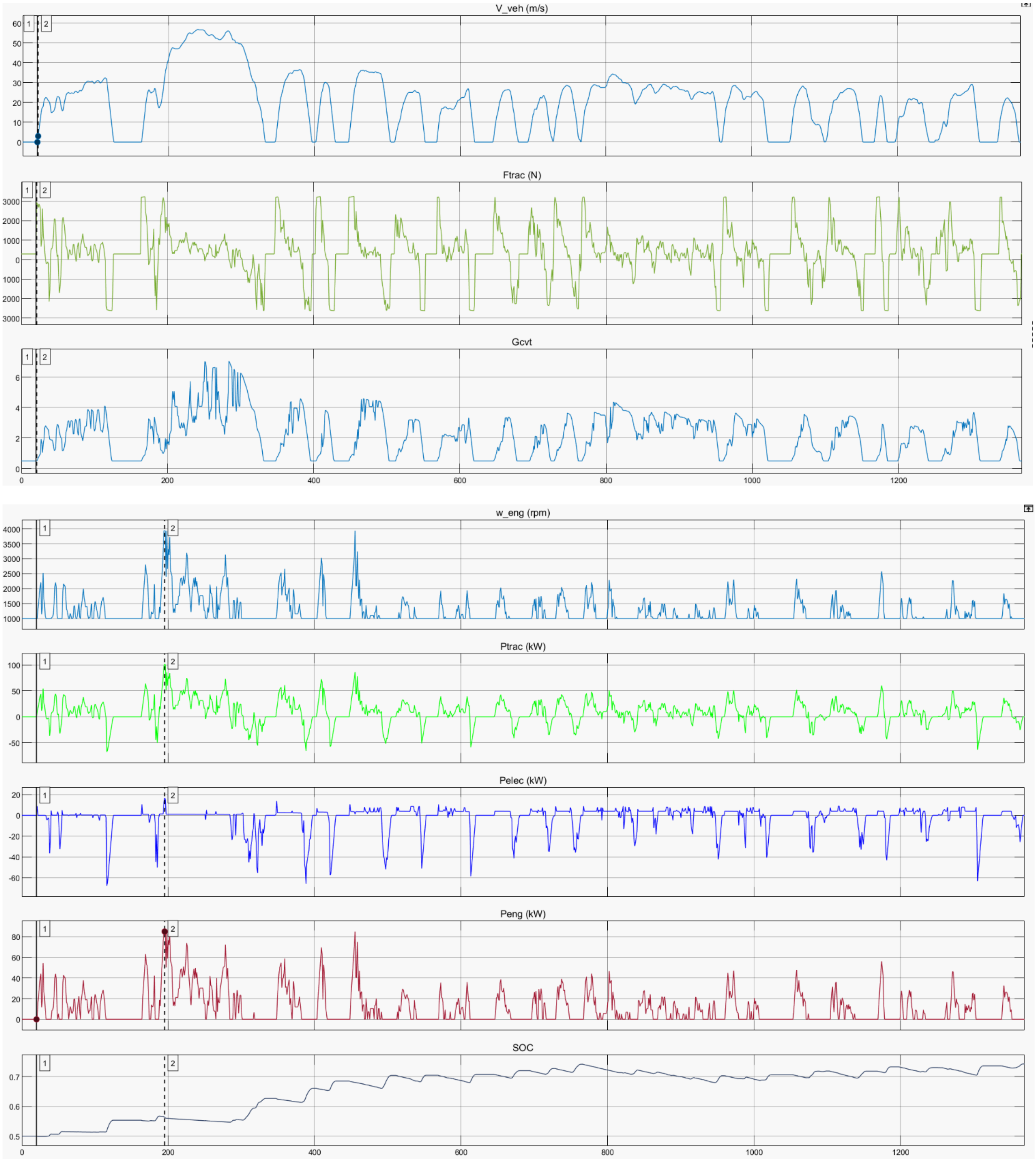


Figure 6 Plots obtained for UDDS (city)

The minimum, maximum and the average values based on the plots are given in the Table 4. These values are obtained from *signal statistics* inside the scope. They can be accessed as follows: In scope, go to *Tools* > *Measurements* > *Signal Statistics.*

Let us verify the power management strategy from the plot. This verification is done only on one drive cycle and will hold true for all the drive cycles used.

1. Electric Launch Mode

From the plot below, we can see that all values are zero and SOC is at 0.5 till T = 20s. At T = 21s, V_{veh} = 3 m/s, Gcvt = 0.5, P_{eng} = 0, P_{trac} = P_{elec} = 8.825 kW. Here, $V_{veh} < V_{veh\_min}$ and $G_{cvt} = G_{cvt\_min}$ = 0.5. This is the electric launch mode. The zoomed plot is shown by Figure 7 below. In this plot, the black vertical line highlights T = 20s and the dotted vertical line highlights T = 21s.

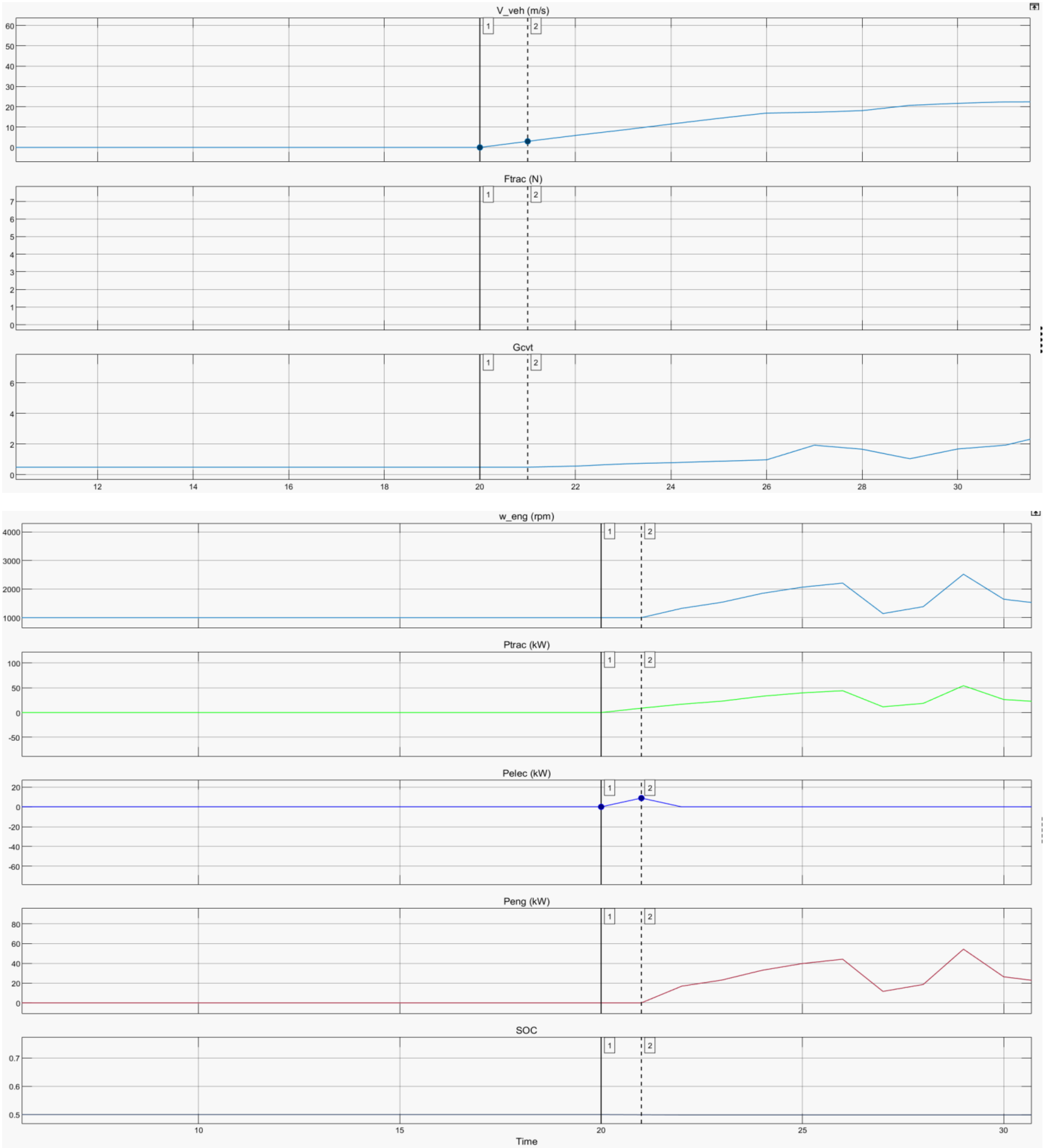


Figure 7 Plots to verify electric launch mode

2. All Electric Mode

This mode can be verified by looking at the plot during T = 40s. At this point, V_{veh} = 14.90 m/s > V_{veh_min} = 3.92 m/s. P_{trac} = 4.6 kW < P_{eng_min}. At this stage, clutch is engaged but no fuel is provided to engine. Hence P_{eng} should be zero which is verified by the plot and P_{trac} = P_{elec}. W_{eng} = 1000 rpm which is equal to W_{eng_min}. In the Figure below, T = 40s is marked by the vertical black line

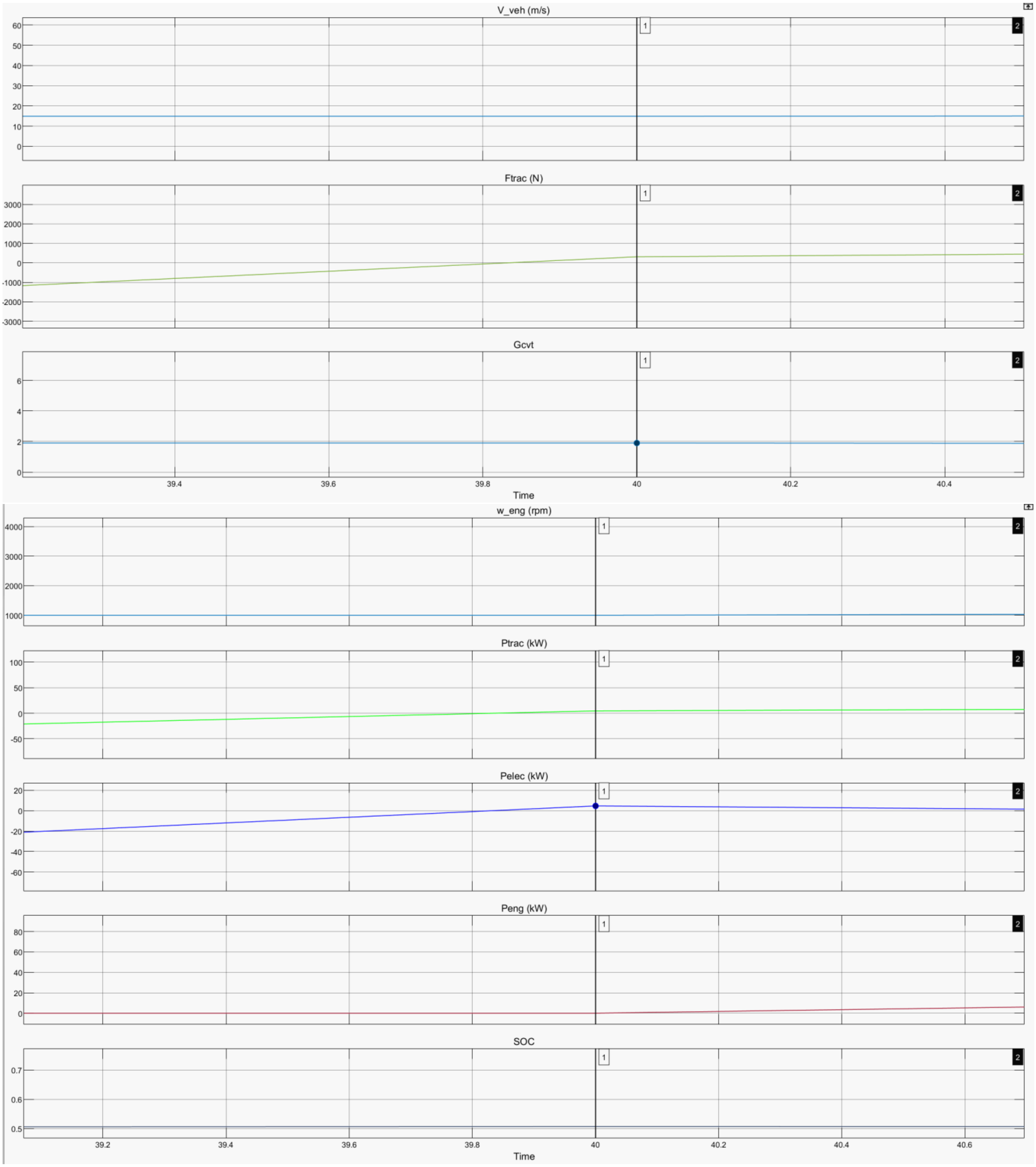


Figure 8 Plots to verify all electric mode

3. Electric Boost Mode

At T = 195s, we see from Figure below that P_{trac} is 101.6 kW. This is the electric boost mode. We can see that at this point, $P_{eng} = P_{eng\_max} = 85$ kW. $P_{elec} = P_{trac} – P_{eng} = 101.6 – 85 = 16.6$ kW. Hence, the electric boost mode is verified as well

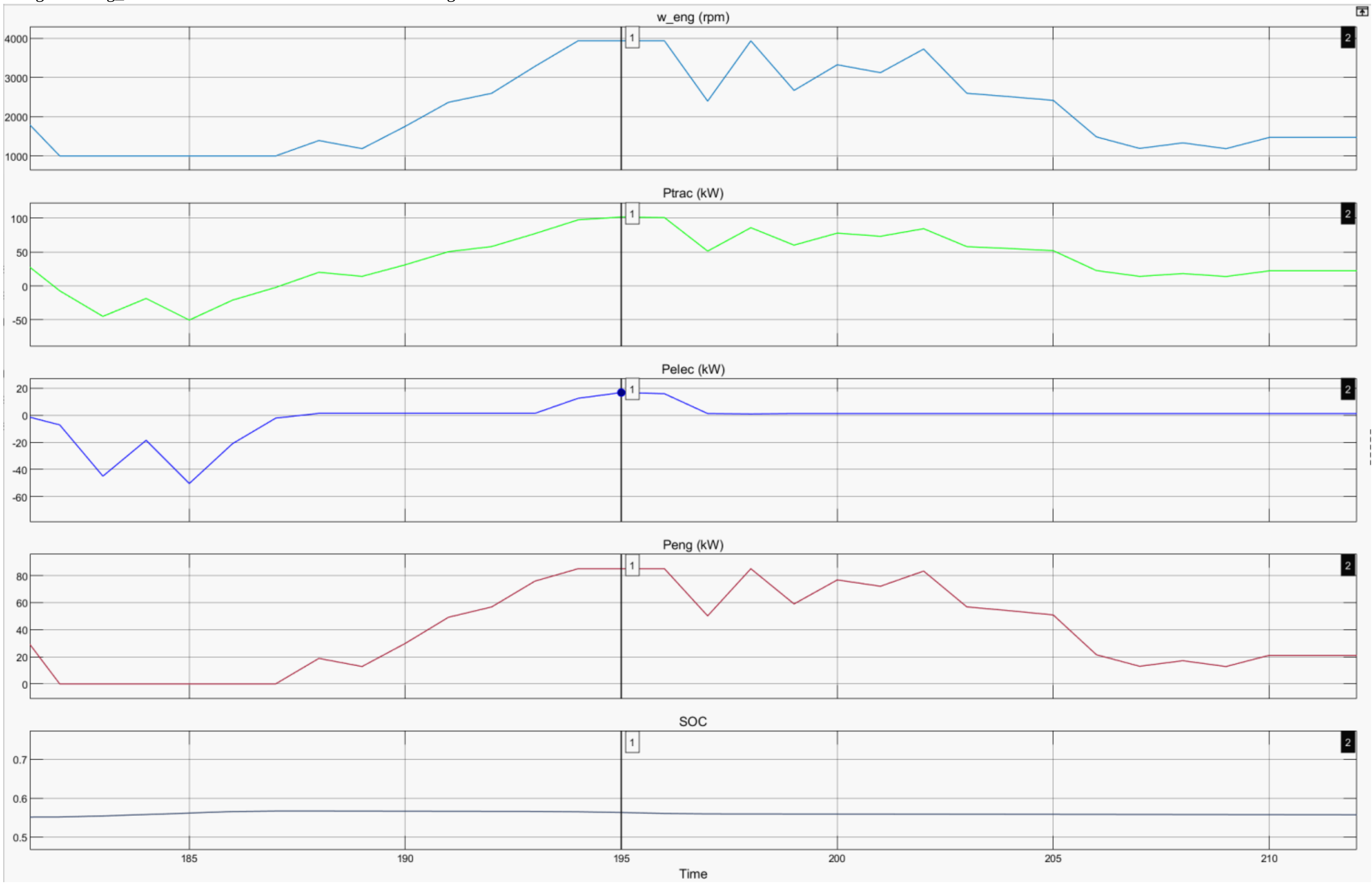


Figure 9 Plots to verify electric boost mode

For the drive cycle, the engine speed (W_{eng}) lies between 1000 rpm (W_{eng_min}) and 3933 rpm. The max SOC is achieved at the end of the drive cycle at 0.742. Thus, the deviation from the target is 0.242. Maximum value for the gear ratio G_{cvt} is 7.04. The average value of Peng is 10.42 kW. The BSFC at this point is given by the MATLAB command bsfc = interp1(eng_map(:,2), eng_map(:,3), P_eng/1000, 'pchip', 'extrap'). Substituting $P_{eng} = 10.42$ kW, we see that the bsfc at this point is 437.7503 g/kWh. It can be seen from the Figure that for areas where P_{trac} and P_{elec} are both negative, P_{eng} is capped at 0 kW. The maximum value of P_{eng} is 85 kW.

The total tractive energy is calculated to be 3.171 kJ. The energy supplied by the engine is calculated to be 3.964 kJ and the energy from the ESS is calculated to be -0.7933 kJ. It can be clearly seen that the first law of thermodynamics is satisfied. $E_{out} = E_{trac} = 3.171$ kJ. Ein = $E_{eng} + E_{ess} = 3.964 – 0.7933 = 3.17$ kJ. Total miles travelled at the end of the cycle is 7.45 miles, the SOC at the end of the cycle is 0.7421. Finally, the average miles per gallon is calculated to be 17.45 miles/gallon. To obtain a converged value, total simulation time is taken to be 50000s.

Table 4 Values calculated for UDDS

Variables	Min	Max	Average	Time (s) when variable is (min)	Time (s) when variable is (max)
V_{veh} (m/s)	0	56.7	21.6	multiple	240
F_{trac} (kN)	-2.624	3.263	0.34	552	455
W_{eng} (rpm)	1000	3933	1240	0-20	194
P_{trac} (kW)	-68.07	101.6	8.333	116	195
P_{elec} (kW)	-68.07	16.63	-2.08	116	195
P_{eng} (kW)	0	85	10.42	multiple	195
SOC	0.498	0.742	0.662	22	1369
G_{cvt}	0.5	7.04	2.125	multiple	284

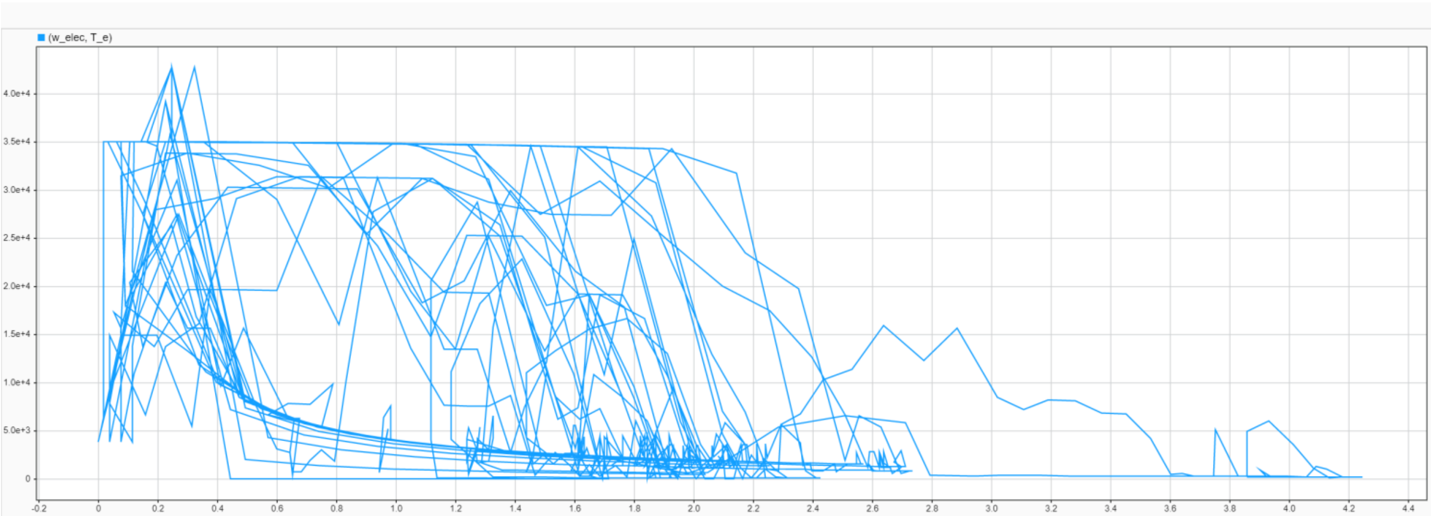
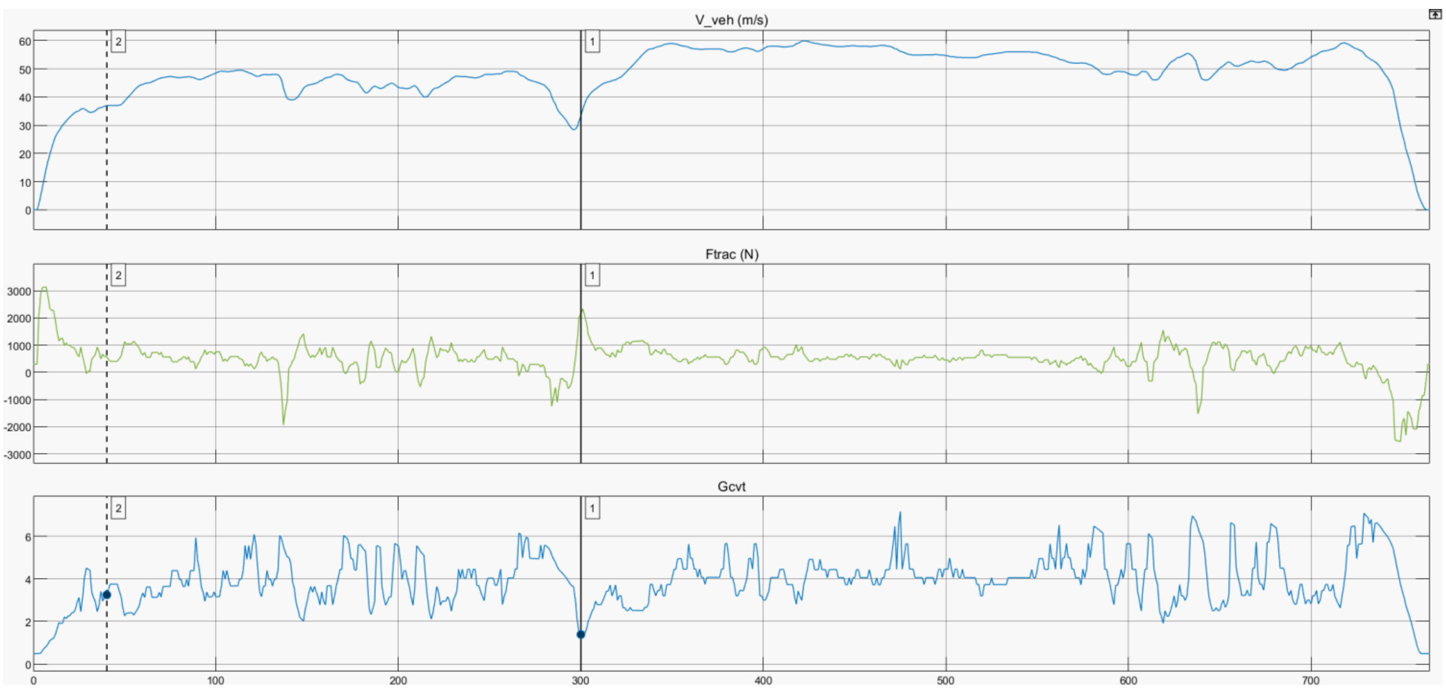


Figure 10 motor torque (N-m) versus its speed (rad/s) for UDDS

HWFET (highway)

This drive cycle highlights the driving conditions in the highway. For the simulation, the simulation time is set to 765 seconds



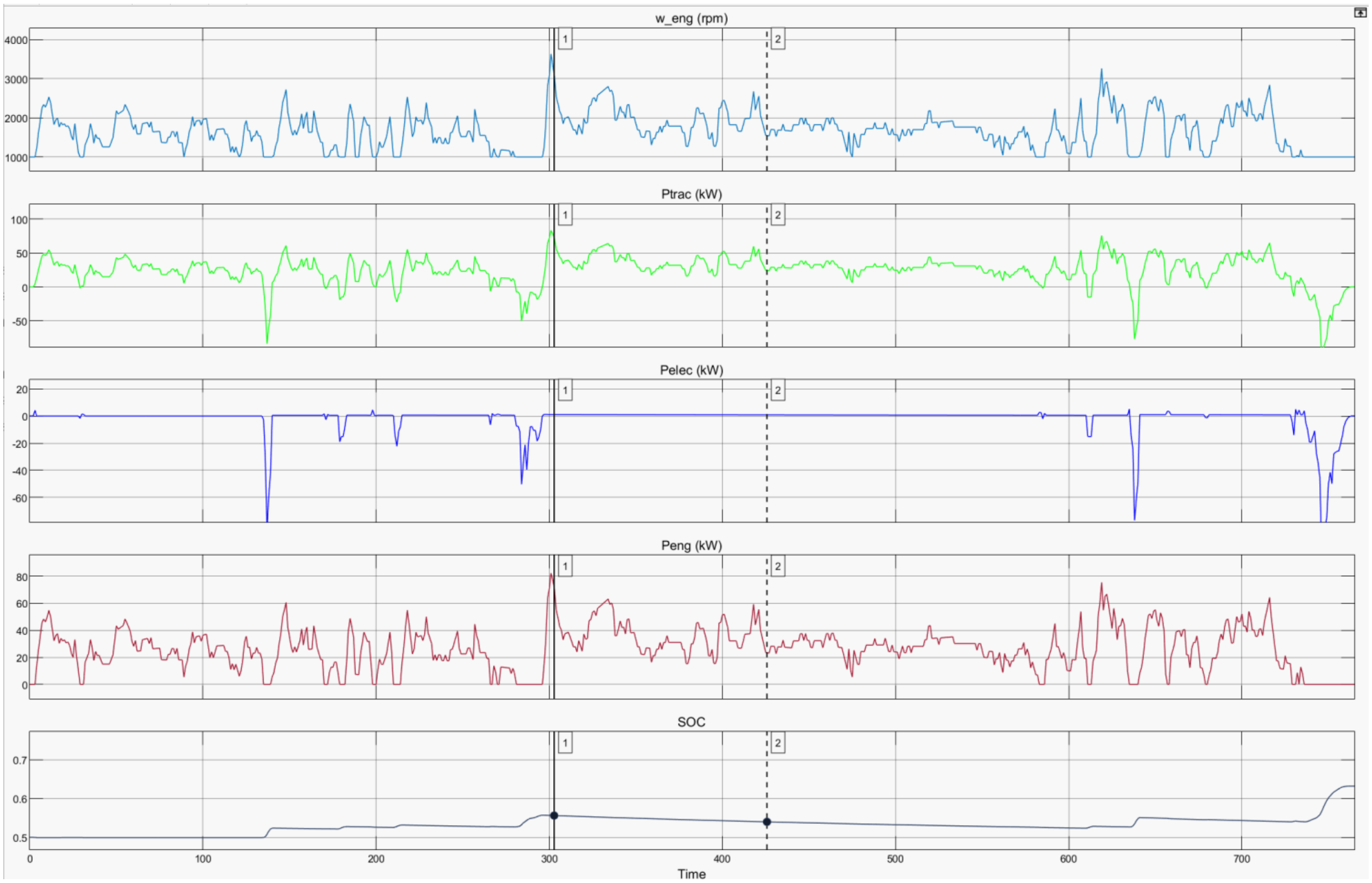


Figure 11 Plots obtained for HWFET (highway)

For this drive cycle, the engine rpm lies between 1000 rpm and 3629 rpm. The maximum SOC is achieved at the end of the drive cycle with a value of 0.632, with the average at 0.5317.Its deviation from the target value is 0.132. The maximum value of the gear ratio G_{cvt} is 7.154. The average value of P_{eng} is 26.23 kW. The BSFC at this point is 313.4796 g/kWh. The maximum value of P_{eng} is 82.14 kW. For the time when both P_{trac} and P_{elec} is negative, P_{eng} is capped to 0 kW. Also, it can be noted that the power requirement is maximum at T = 301s where P_{trac} is 83.27 kW, P_{elec} is 5.16 kW and P_{eng} is 82.14 kW. We also note that the average value of P_{elec} is -1.696 kW while average value of P_{eng} is significantly higher at 26.23 kW. This highlights the fact that most of the required power was given by the engine and not the motor. This is to be expected since the drive cycle is in the highway at higher speeds. If we compare the average velocity of the drive cycle in the highway to the drive cycle in the city, we see that the average speed is about 48.2 m/s while the average speed in the city is 21.6 m/s.

The total tractive energy is calculated to be 5.22 kJ. The energy supplied by the engine is calculated to be 5.581 kJ and the energy from the ESS is calculated to be -0.3608 kJ. It can be clearly seen that the first law of thermodynamics is satisfied. $E_{out} = E_{trac}$ = 5.22 kJ. Ein = $E_{eng} + E_{ess}$ = 5.581 – 0.3608 = 5.22 kJ. Total miles travelled at the end of the cycle is 10.26 miles, the SOC at the end of the cycle is 0.632. Finally, the average miles per gallon is calculated to be 17.33 miles/gallon. To obtain a converged value, total simulation time is taken to be 50000s.

Table 5 Values calculated for HWFET

Variables	Min	Max	Average	Time (s) when variable is (min)	Time (s) when variable is (max)
V_{veh} (m/s)	0	59.90	48.20	0	422
F_{trac} (kN)	-2.553	3.135	0.4916	749	7
W_{eng} (rpm)	1000	3629	1669	multiple	301
P_{trac} (kW)	-97.89	83.27	24.53	746	301
P_{elec} (kW)	-97.89	5.16	-1.696	746	635
P_{eng} (kW)	0	82.14	26.23	multiple	301
SOC	0.4993	0.632	0.5317	32	763
G_{cvt}	0.5	7.154	3.928	0	478

The motor torque (N-m) versus its speed (rad/s) is plotted below.

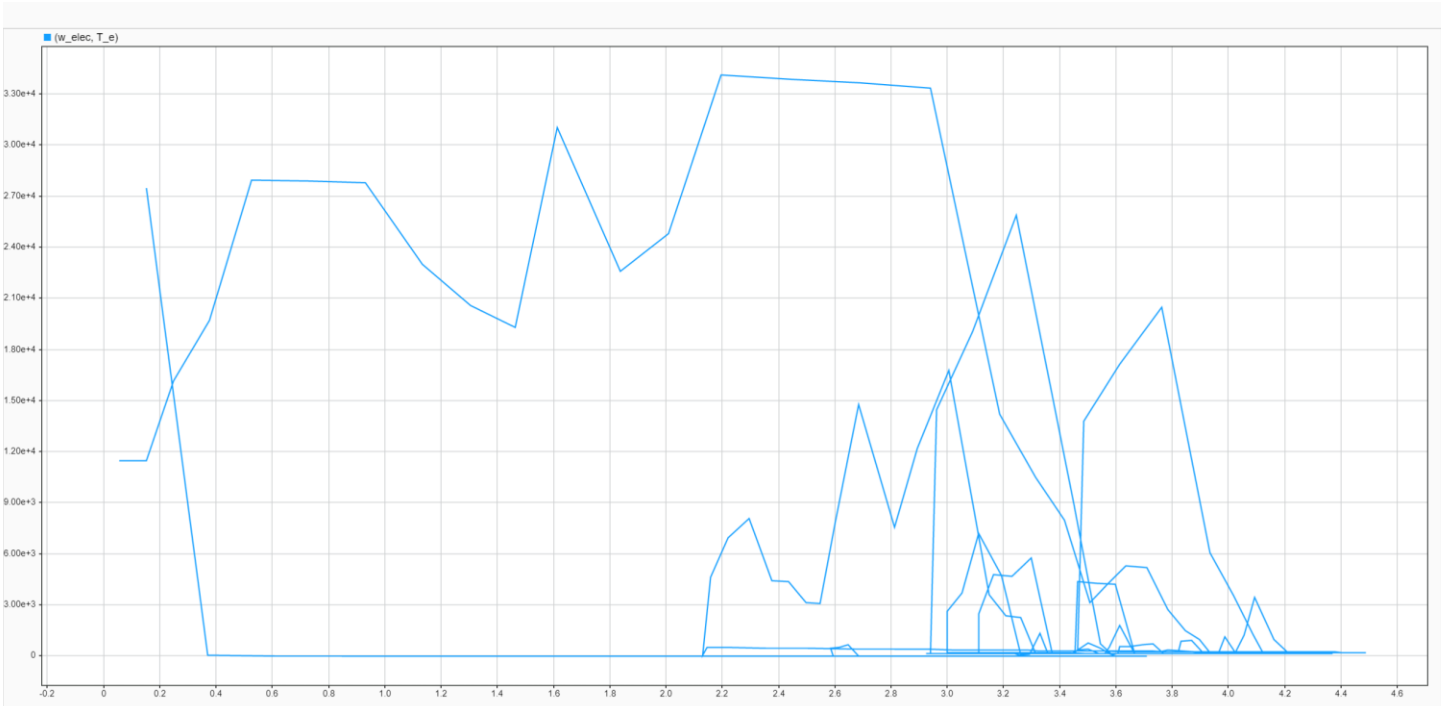


Figure 12 motor torque (N-m) versus its speed (rad/s) for HWFET (highway)

US06 (aggressive highway)

This drive cycle highlights the driving conditions in the aggressive highway. For the simulation, the simulation time is set to 596 seconds

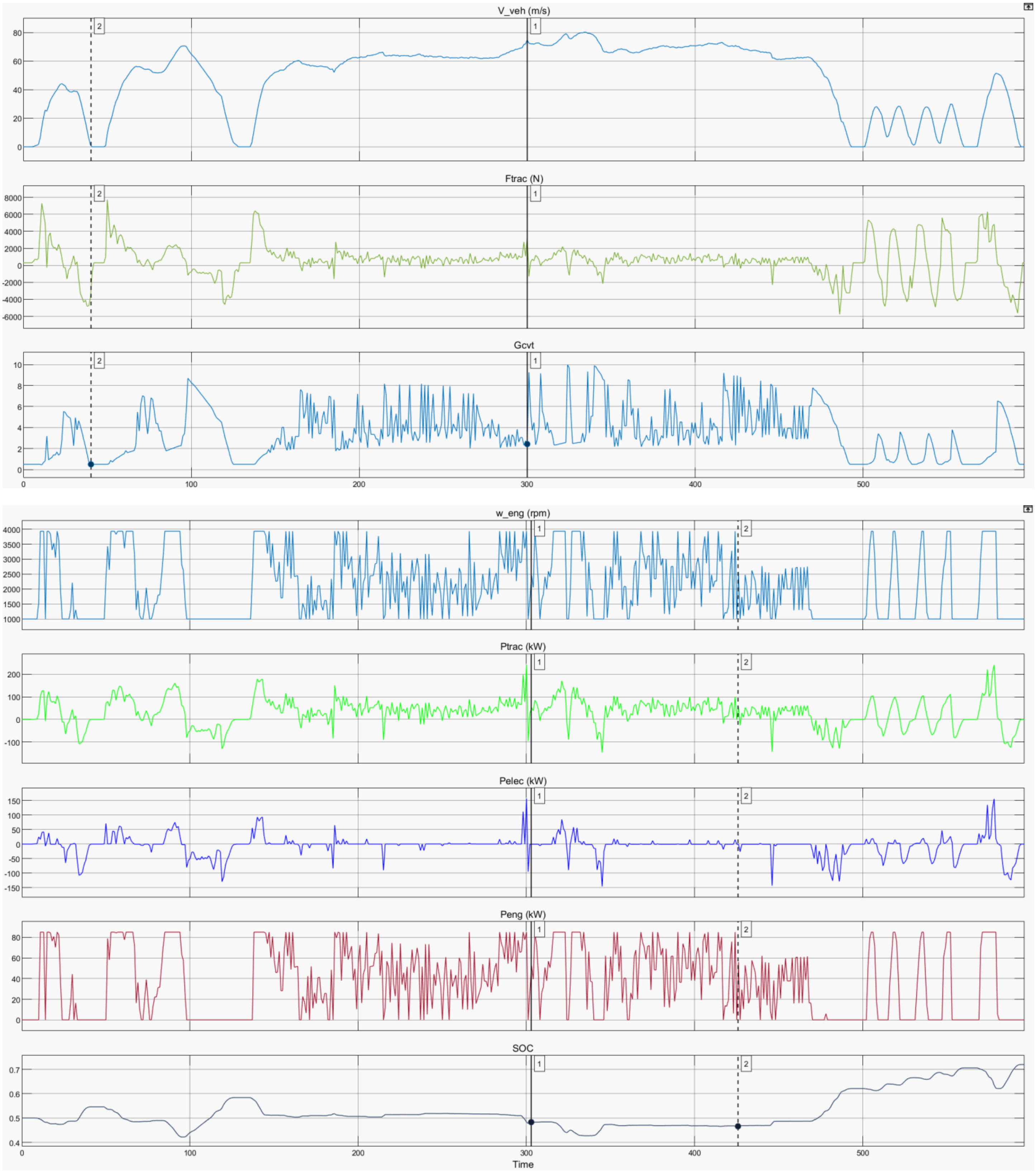


Figure 13 Plots obtained for US06 (aggressive highway)

For this drive cycle, w_{eng} lies between 1000 rpm and 3933 rpm, with the average value being 2110 rpm. This value is higher than the w_{eng} of city and highway which is to be expected since this drive cycle is an aggressive highway category. We can also see that the power requirements are significantly higher than the highway and city. The maximum SOC is achieved almost at the end of the drive cycle with the value of 0.7199 and the maximum value of G_{cvt} is 9.973. The average value of P_{eng} is 36.44 kW and the BSFC at this point is given by 283.54 g/kWh. For the time when both P_{trac} and P_{elec} is negative, P_{eng} is capped to 0 kW. Also, it can be noted that the power requirement is maximum at T = 300s where P_{trac} is 241.8 kW, P_{elec} is 156.8 kW

The total tractive energy is calculated to be 5.239 kJ. The energy supplied by the engine is calculated to be 6.043 kJ and the energy from the ESS is calculated to be -0.8039 kJ. It can be clearly seen that the first law of thermodynamics is satisfied. $E_{out} = E_{trac} = 5.239$ kJ. $E_{in} = E_{eng} + E_{ess} = 6.043 – 0.8039 = 5.239$ kJ. Total miles travelled at the end of the cycle is 8.01 miles, the SOC at the end of the cycle is 0.7199. Finally, the average miles per gallon is calculated to be 14.62 miles/gallon. To obtain a converged value, total simulation time is taken to be 50000s.

Table 6 Values calculated for US06

Variables	Min	Max	Average	Time (s) when variable is (min)	Time (s) when variable is (max)
V_{veh} (m/s)	0	80.30	59.70	0	334
F_{trac} (kN)	-5.763	7.718	0.5325	486	50
W_{eng} (rpm)	1000	3933	2110	0	11
P_{trac} (kW)	-145.9	241.8	31.59	345	300
P_{elec} (kW)	-145.9	156.8	-4.847	345	300
P_{eng} (kW)	0	85	36.44	0	11
SOC	0.4221	0.7199	0.5262	95	594
G_{cvt}	0.4507	9.973	3.441	11	324

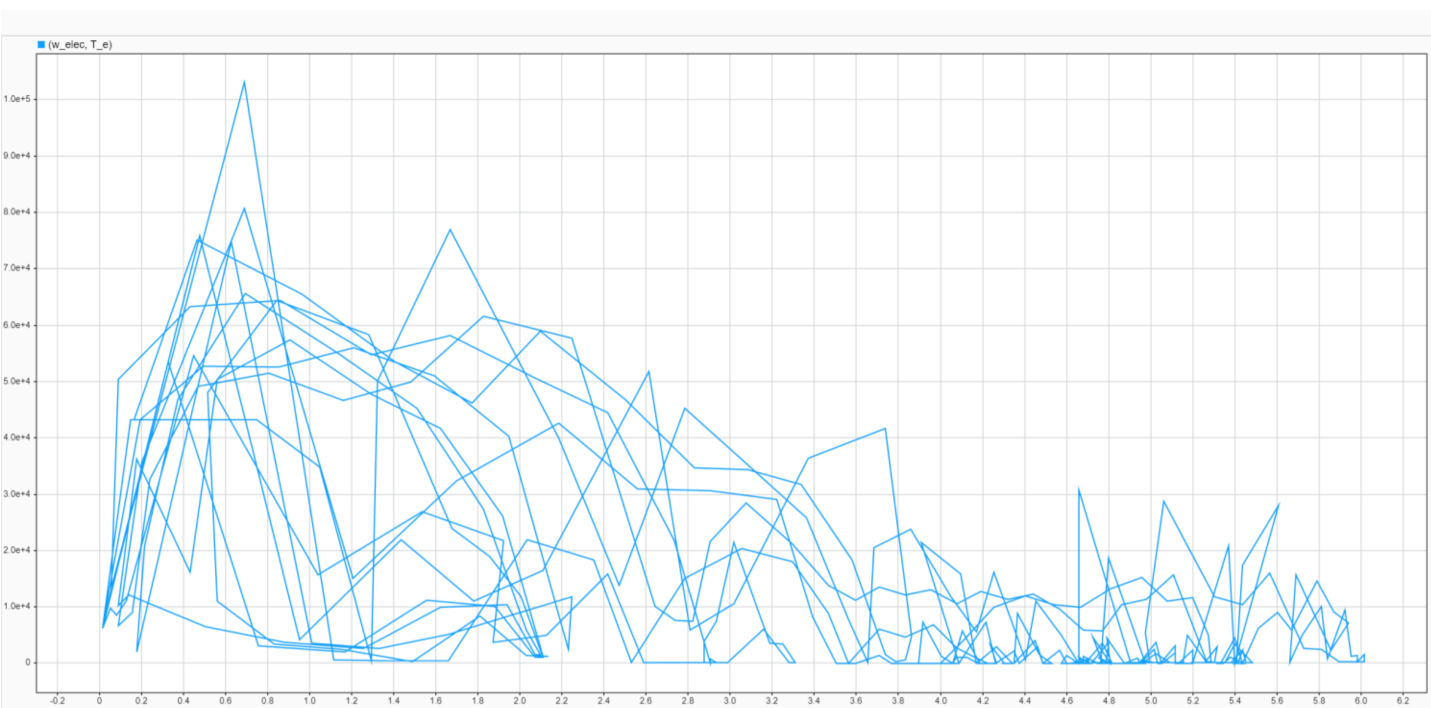


Figure 14 motor torque (N-m) versus its speed (rad/s) for US06

Discussion

The Table below compares different variables for the three drive cycles. If we look at the fuel economy (average miles/gallon), it can be seen that HWFET (highway) and UDDS (city) has almost a similar fuel economy giving about 17.40 miles/gallon while the US06 (aggressive highway) has a worse fuel economy giving only 14.62 miles/gallon. The tractive energy also increases as we go from city to aggressive highway, thus requiring more energy supplied by the engine. We also see that the max G_{cvt} increases as we go from city to highway to aggressive highway. A higher gear ratio means that it

strives to decrease the engine speed to a minimum thereby keeping making the vehicle more fuel efficient. This can be confirmed by the decreasing BSFC values as we go from city to aggressive highway. We can also see that the energy losses from drag and rolling resistance increases. This is to be expected since the average velocity increases from the city to highway. The regenerative energy is calculated by integrating the negative values of P_{trac} over the duration of the drive cycle. The highest absolute value of this energy is found at the us06 drive cycle. Hence, we can conclude that the energy recouped is better in the aggressive highway compared to the city. If we calculate the proportion of energy recouped from the total energy supplied by the engine and the ESS, the percentage recouped can be calculated as follows:
Proportion of energy recouped = abs((Regenerative energy)/(Total tractive energy))*100
For UDDS (city): 48.7 %
For HWFET (highway): 9.26 %
For US06 (aggressive highway): 34.3 %.
Hence, we can conclude that the energy recouped is better in the city.

Table 7 Values compared for the three drive cycles

	UDDS(city)	HWFET(highway)	US06 (aggressive highway)
Total tractive energy (kJ)	3.171	5.22	5.239
Energy supplied by engine (kJ)	3.964	5.581	6.043
Energy supplied by ESS (kJ)	-0.7933	-0.3608	-0.8039
Energy lost due to drag (kJ)	0.3023	0.9815	1.141
Energy lost to ESS (kJ)	0.309	0.09677	0.364
Energy lost to rolling resistance (kJ)	0.9684	1.333	1.041
Total fuel used (gal)	0.4463	0.5852	0.5834
Total miles travelled	7.45	10.26	8.01
Average miles per gallon	17.45	17.33	14.62
SOC at end of cycle	0.7421	0.632	0.7199
Max G_{cvt}	7.04	7.154	9.973
BSFC at average engine power (g/kWh)	437.7503	313.4796	283.54
Regenerative energy (kJ)	-1.545	-0.4834	-1.797

Appendix

1. Init.m

```
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 ;
```

2. 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 = 20000*(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
```