Project 1: Analysis of a Parallel Hybrid Electric Vehicle

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Abstract

In this project, the force and power flow through a parallel hybrid electric vehicle was modeled and analyzed in Simulink. The internal combustion engine (ICE) is used for sustained operation and always operates in its optimum fuel efficiency regime, while the electric power systems are used only for launch, boost, and regenerative braking. Throughout three common drive schedules, the simulated vehicle's ICE and electric power systems were monitored, and the model provided reasonable and realistic results.

Introduction

Hybrid electric vehicles enable more efficient management of energy used for transporting people and goods, leading to increased fuel efficiency compared to conventional vehicles with only internal combustion engines (ICE) (Mi and Masrur 2017). In this paper, a hybrid electric vehicle is put through several simulated driving conditions and relevant parameters are recorded, such as torque-speed in the electric motor and the flow of power into, through, and out of the system. The overall architecture of this simulated vehicle is given in Figure 1. It is a parallel hybrid vehicle, which means that the ICE is mechanically connected to the wheels, and the electric machine is attached to the same driveshaft.

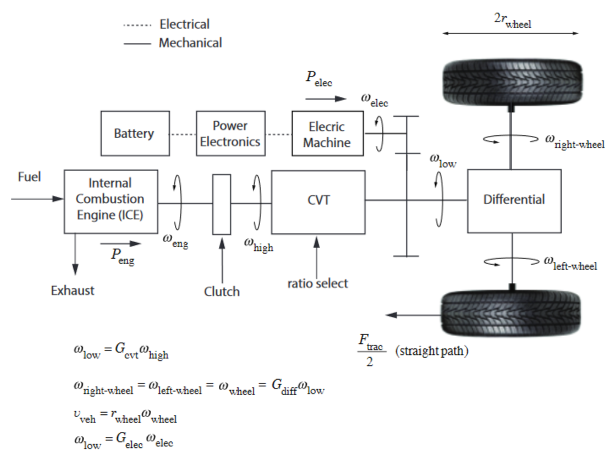

Figure 1: The system architecture of the parallel hybrid electric vehicle. The electric motor/generator is connected to the driveshaft between the continuously variable transmission (CVT) and the differential (Alothman 2023).

Methods

The vehicle and its behavior was analyzed using Simulink. Constants such as “M_veh” or “eta_ess” were initialized using a script given in the appendix. The model used is shown in Figure 2.

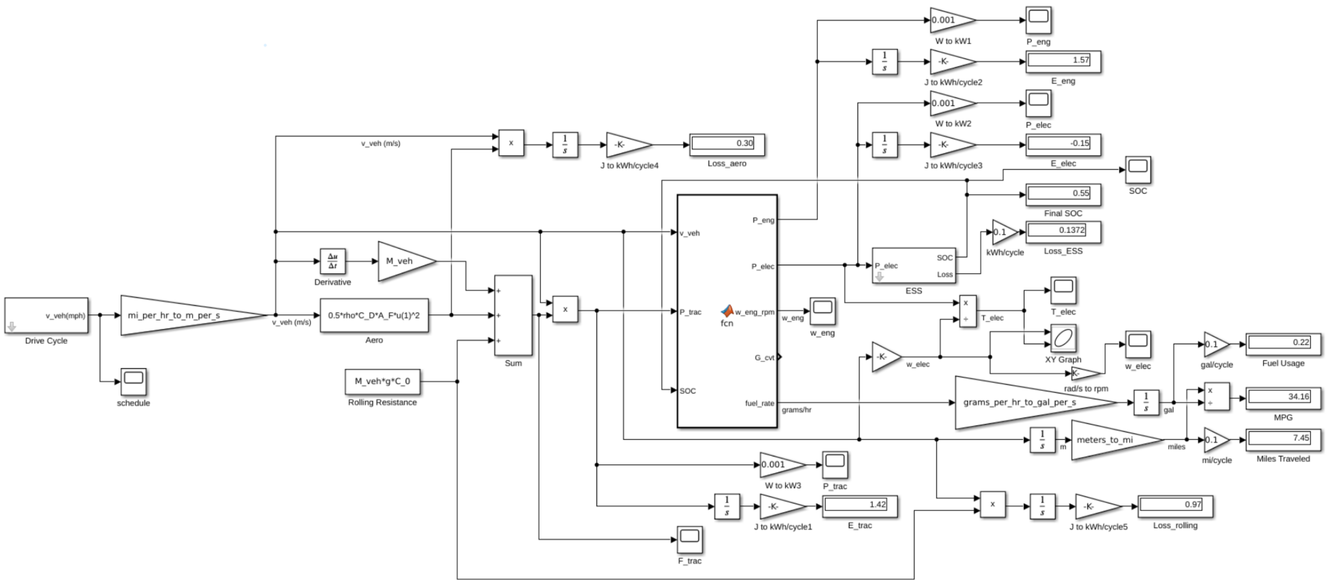

Figure 2: The Simulink model of the vehicle. The interior of the ESS block is shown in Figure 3, and the code running inside the "fcn" block is reproduced in the appendix.

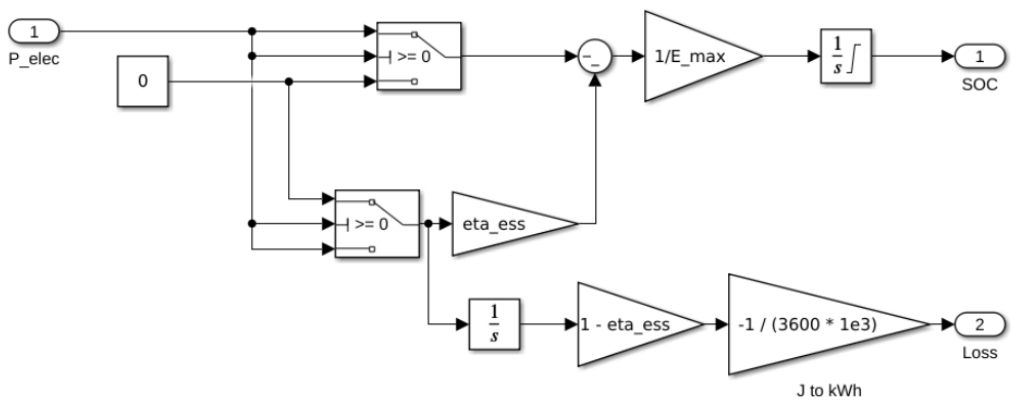

Figure 3: The internal function of the ESS block in the Simulink model.

The simulation was performed for three different drive schedules published by the United States EPA: "UDDS" (a typical city drive), "HWFET" (a typical highway drive), and "US06" (an aggressive highway drive). For each drive schedule, ten plots were generated: one showing the drive schedule itself, one showing the torque-speed relationship for the electric machine, and eight others showing how various vehicle parameters varied throughout the drive. In addition, ten physical quantities were calculated for each drive schedule and tabulated in Table 1. Of those quantities, all but the state of charge (SOC) were found by running the simulation for the drive cycle ten times in a row and finding the average value. The SOC value and the plots were generated by running the simulation for a single drive cycle.

Results & Analysis

UDDS (City)

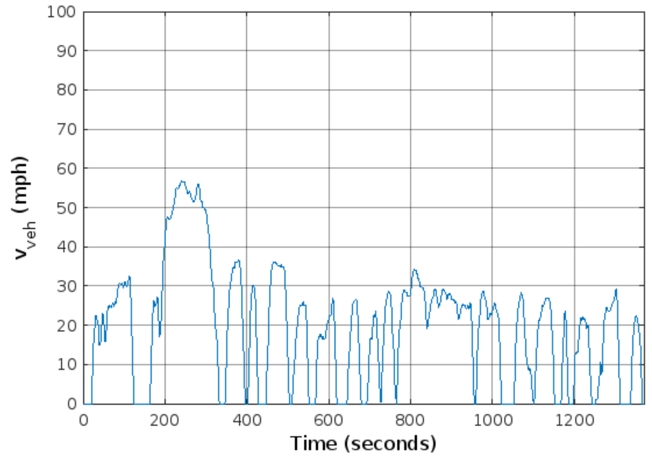

Figure 4: EPA Urban Dynamometer Driving Schedule (UDDS) (United States EPA 2022).

In this drive schedule, frequent stops and starts require the vehicle to accelerate and decelerate quite often. The total tractive force and power requirements for this drive schedule are shown in Figure 5.

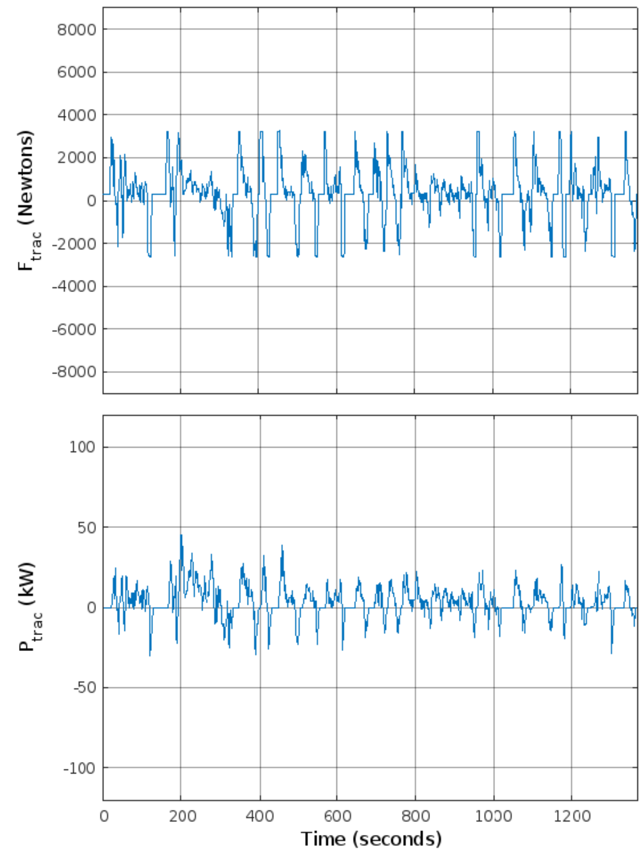

Figure 5: Tractive force and power requirements for the UDDS simulation. Values frequently alternate between positive and negative as the vehicle stops and starts in city traffic.

The vehicle's gasoline engine speed and power output are shown in Figure 6.

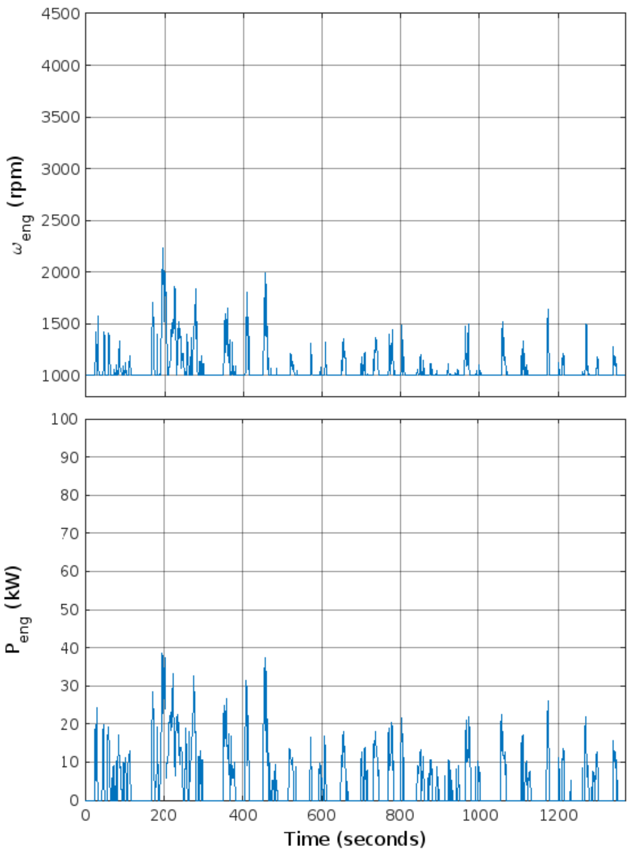

Figure 6: ICE speed and power output for the UDDS simulation. Power output is made up of sporadic spikes where the vehicle must accelerate from a stop, often surrounding periods at zero engine power, where “electric launch mode” propels the vehicle using only the battery at low speeds.

The vehicle’s electric machine torque, speed, and power output are shown in Figure 7. The sharp-eyed viewer may notice that the electric machine speed is directly proportional to the vehicle’s ground speed (as shown in Figure 4); this is because the electric machine is connected to the driveshaft after the transmission, so the gear ratio never changes.

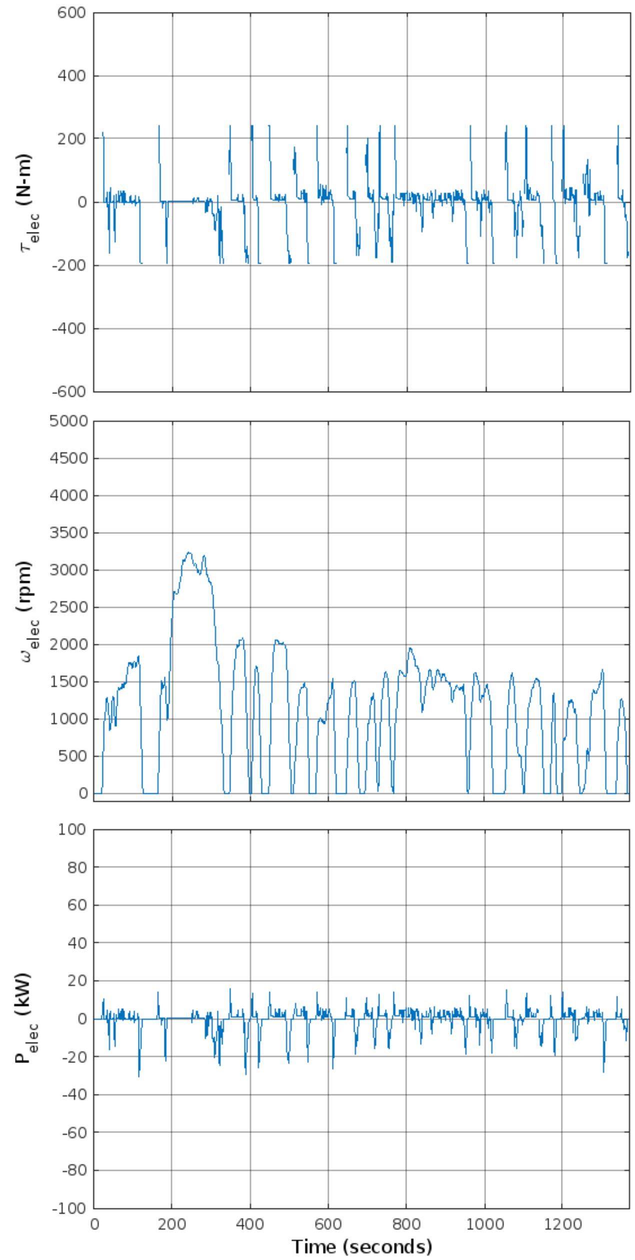

Figure 7: Electric machine torque, speed, and power output for the UDDS simulation. Both torque and power have several spikes that take them negative; each spike corresponds to a period of regenerative braking, which is common in these stop-start city-driving conditions.

A torque-speed plot for the vehicle’s electric machine is given in Figure 8.

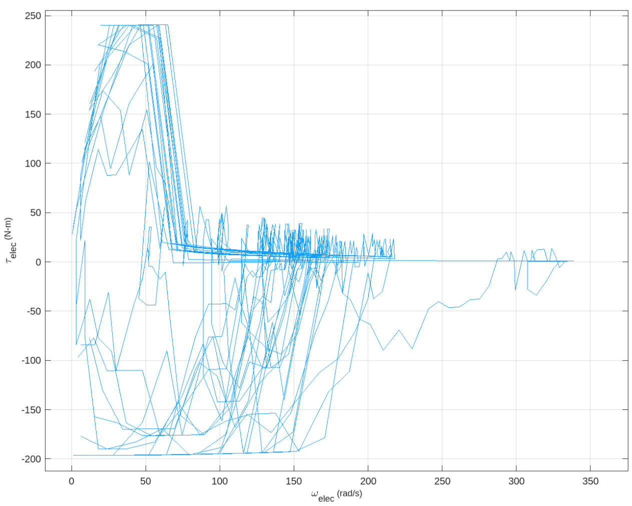

Figure 8: Electric machine's torque-speed plot for the UDDS simulation. While messy, it shows that most traces are in the low-speed, high-torque regions, as expected for city driving at low average speed. The large number of traces with negative torque show that regenerative braking was a frequent occurrence.

Finally, the state of charge for the energy storage subsystem (ESS), or battery, is shown in Figure 9.

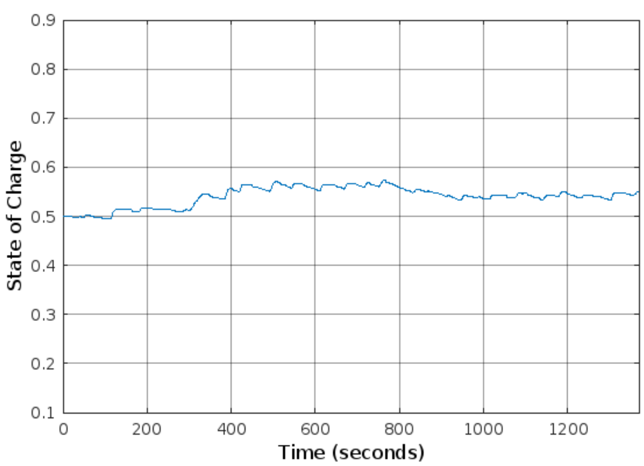

Figure 9: SOC throughout the UDDS simulation. The frequently alternating charge and discharge cycles correspond to the frequent electric launch and regenerative braking that occur during stop-start city traffic.

HWFET (Highway)

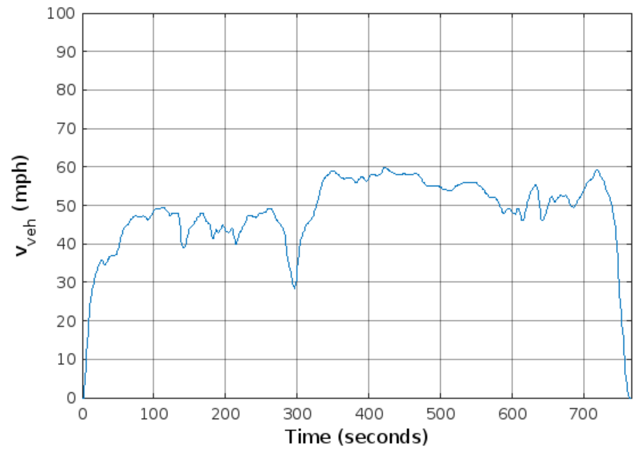

Figure 10: Highway Fuel Economy Driving Schedule (HWFET) (United States EPA 2022).

In this drive schedule, most of the journey is spent cruising at relatively consistent high speeds, such that acceleration and deceleration are fairly infrequent. The total tractive force and power requirements for this drive schedule are shown in Figure 11.

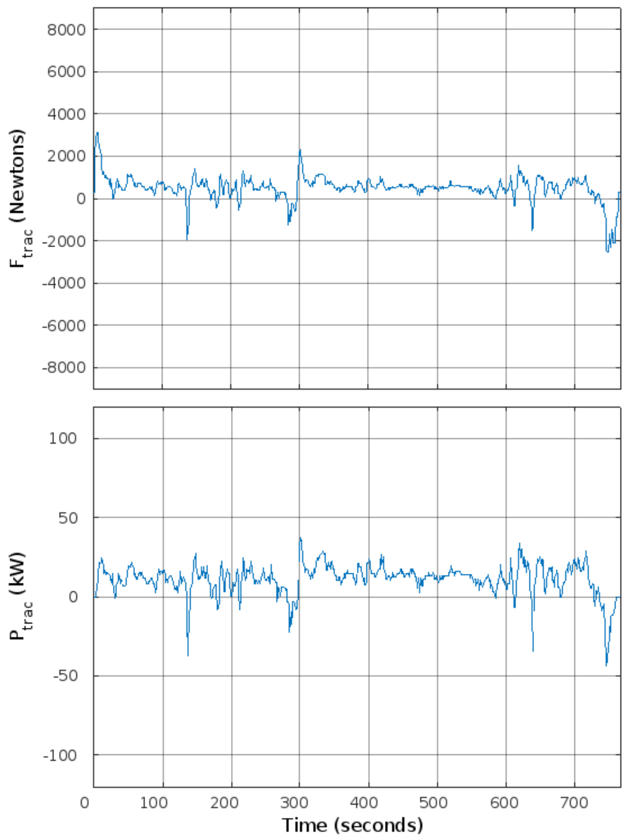

Figure 11: Tractive force and power requirements for the HWFET simulation. Values are fairly constant, with large changes only at the beginning and end, when the vehicle accelerates to and decelerates from highway speeds. There is also one additional spike at about 300 seconds, corresponding to when the vehicle accelerates from a high speed to an even higher speed.

The vehicle's gasoline engine speed and power output are shown in Figure 12.

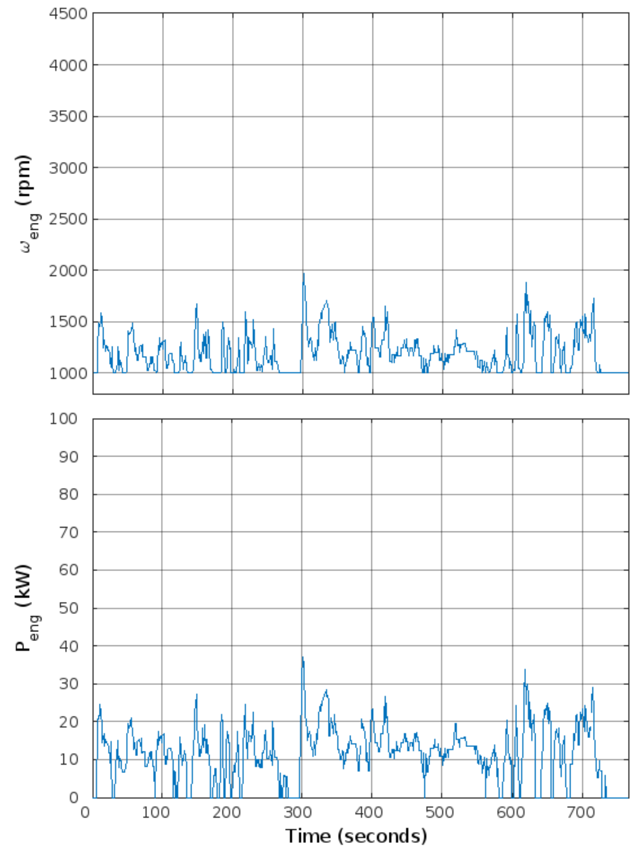

Figure 12: ICE speed and power output for the HWFET simulation. Both quantities stay in about the same range throughout the test, with one large spike at about 300 seconds, corresponding to when the vehicle accelerates from a high speed to an even higher speed.

The vehicle's electric machine torque, speed, and power output are shown in Figure 13. As in the UDDS simulation, and for the same reason, the electric machine speed is directly proportional to the vehicle's ground speed (Figure 10).

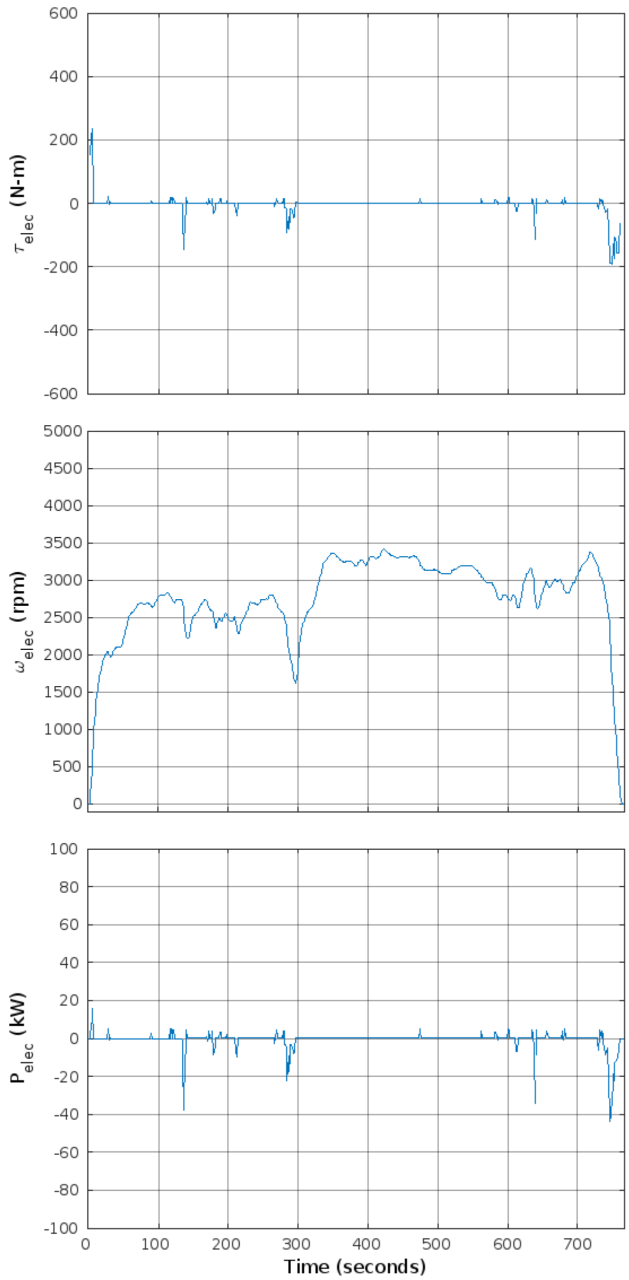

Figure 13: Electric machine torque, speed, and power output for the HWFET simulation. Since most of this drive schedule is spent at a fairly constant speed, the electric machine is not used very much; only a few small instances of regenerative braking during the drive, followed by a more significant period of regenerative braking when the vehicle decelerates at the end.

A torque-speed plot for the vehicle's electric machine is given in Figure 14.

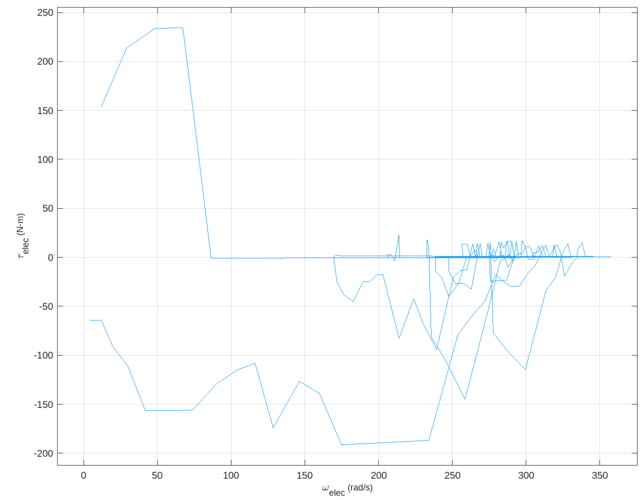

Figure 14: Electric machine's torque-speed plot for the HWFET simulation. While messy, it shows that most traces are in the high-speed, low-torque regions, as expected for steady highway driving at high average speed. The tallest traces having negative torque indicate that regenerative braking was much more common than electric launch or boost.

Finally, the state of charge for the ESS is shown in Figure 15.

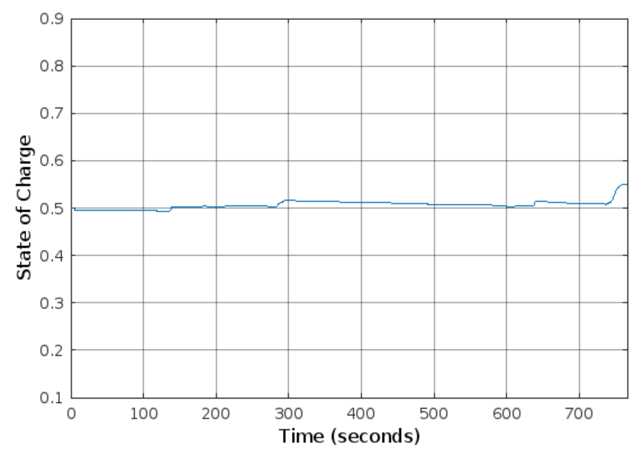

Figure 15: SOC throughout the HWFET simulation. The overall flatness of the plot indicates how infrequently the electric machine was used in this drive schedule. Steps at about 300 seconds and again at the end indicate the only instances of significant regenerative braking.

US06 (Aggressive Highway)

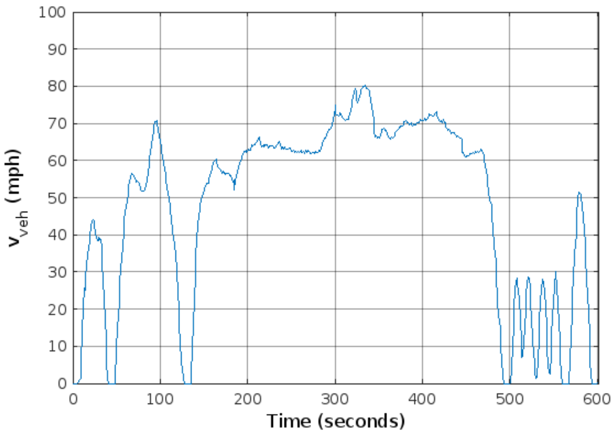

Figure 16: US06, a high acceleration aggressive drive schedule (United States EPA 2022).

In this drive schedule, the vehicle experiences both high speeds, reaching up to 80 miles per hour, as well as many instances of rapid acceleration and braking. The total tractive force and power requirements for this drive schedule are shown in Figure 17.

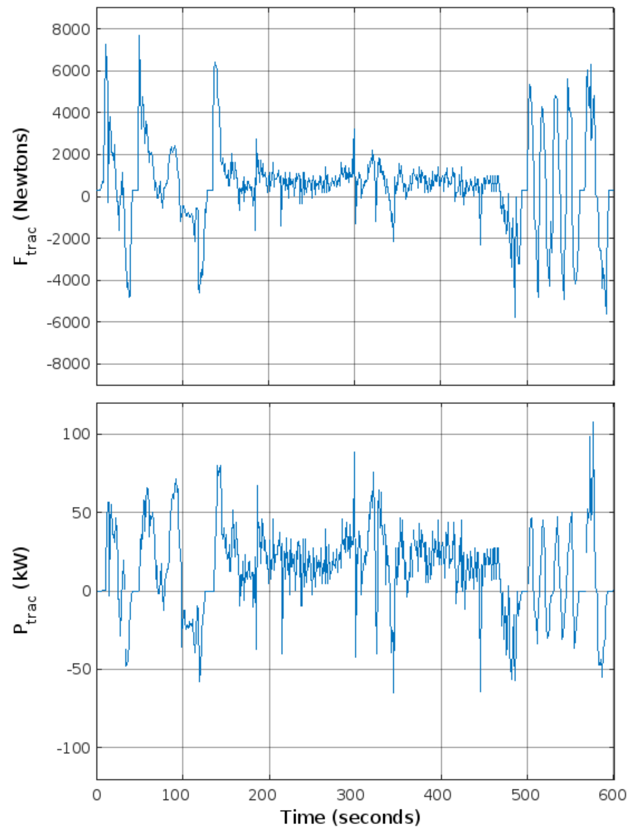

Figure 17: Tractive force and power requirements for the US06 simulation. Large spikes in both positive and negative directions indicate aggressive acceleration and deceleration, as expected from this drive schedule.

The vehicle's gasoline engine speed and power output are shown in Figure 18.

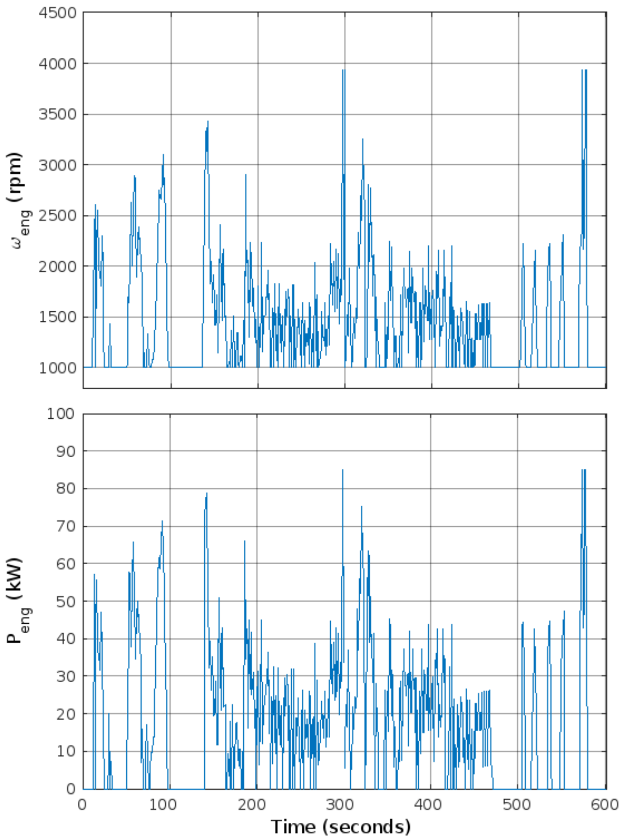

Figure 18: ICE speed and power output for the US06 simulation. Frequent spikes to high speed and power are present, as expected for this aggressive style of driving with regular periods of very high acceleration.

The vehicle's electric machine torque, speed, and power output are shown in Figure 19. As in the previous simulations, and for the same reason, the electric machine speed is directly proportional to the vehicle's ground speed (Figure 16).

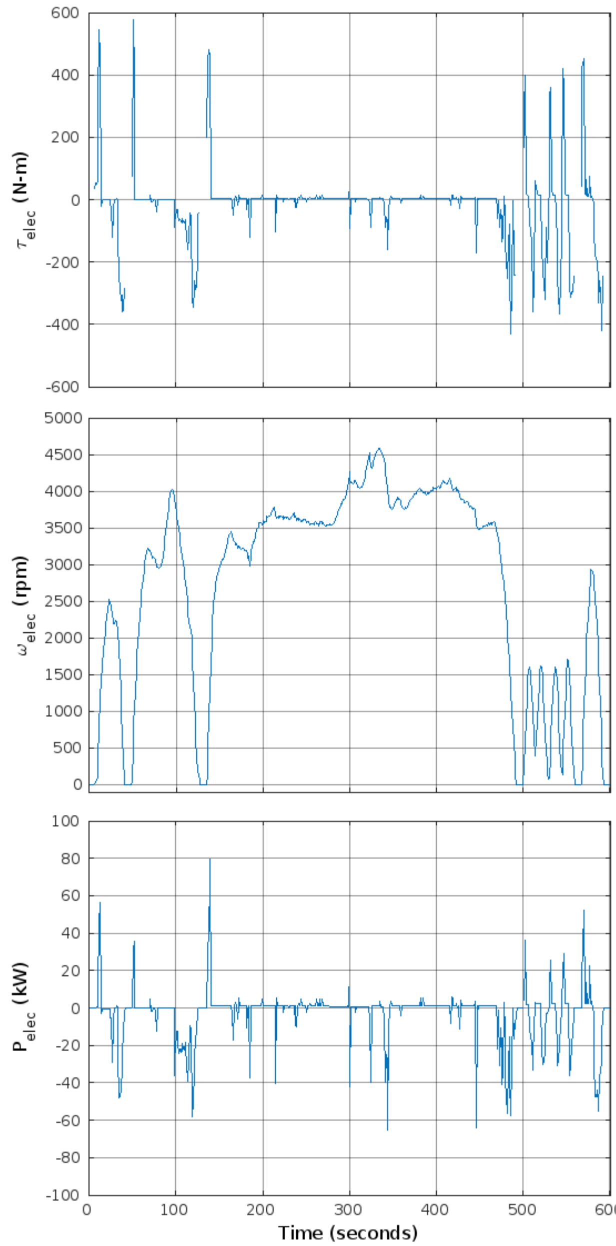

Figure 19: Electric machine's torque, speed, and power output for the US06 simulation. Large spikes in the positive direction indicate use of electric launch and electric boost, both in service of the aggressive acceleration used in this drive schedule, while frequent large spikes in the negative direction indicate the regular use of regenerative braking in service of the aggressive deceleration used in this schedule as well.

A Torque-speed plot for the vehicle's electric machine is given in Figure 20.

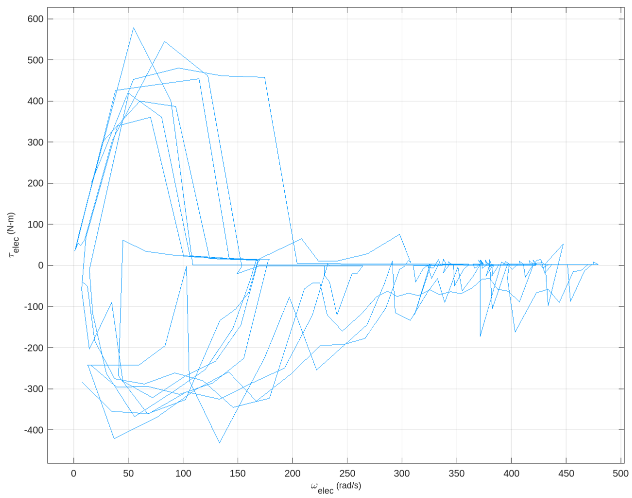

Figure 20: Electric machine's torque-speed plot for the US06 simulation. The fact that there are many traces in nearly all regions of the plot indicate that the driver frequently accelerated and decelerated, and rapidly, throughout the vehicle's entire range of operating speeds.

Finally, the state of charge for the ESS in shown in Figure 21.

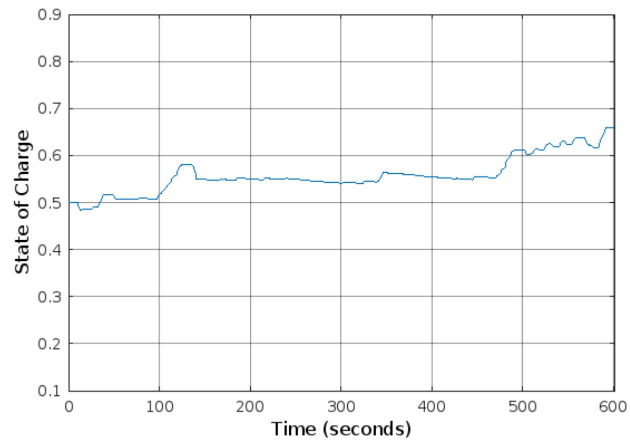

Figure 21: SOC throughout the US06 simulation. A few sharp downturns indicate when electric launch and electric boost were used, while the frequent rapid steps upwards indicate the regular use of aggressive regenerative braking, which also explains why the final SOC is so high.

Summary of Results

Calculated estimates for various important physical quantities are given in Table 1.

Table 1

	UDDS	**HWFET**	**US06**	
Tractive Energy	1.42	2.34	2.34	kWh
Engine Energy	1.57	2.39	2.56	kWh
ESS Energy	-0.15	-0.05	-0.22	kWh
Aerodynamic Loss	0.30	0.98	1.14	kWh
ESS Loss	0.14	0.04	0.16	kWh
Rolling Loss	0.97	1.33	1.04	kWh
Fuel Consumption	0.22	0.33	0.28	gal
Drive Distance	7.45	10.26	8.01	mi
Fuel Efficiency	34.16	31.46	28.95	mpg
Final SOC	0.55	0.55	0.66	

To provide a few brief sanity checks, the Tractive Energy should be equal to the sum of the Engine Energy and the ESS Energy (e.g. 1.42 = 1.57 - 0.15); this is true for all three drive schedules. In addition, that net total energy should be equal to the sum of losses (e.g. 1.42 = 0.30 + 0.14 + 0.97). This is not quite true, as two of the drive schedules are off by 0.01 kWh, but we can safely treat such small differences as rounding errors, so this is not a cause for concern.

Note that if a drive schedule involved stopping at a different velocity than it started, then these calculations would require taking into account the difference in kinetic energy of the vehicle, too. However, all three drive schedules used in this study began and ended at a complete stop, so that net difference was zero in all cases.

Discussion

The results discussed in the previous section all fit within reasonable bounds and lead to conclusions that one would expect based on real-world vehicle behavior; figure captions explain the conclusions that one can derive from each associated plot and why they are reasonable for its drive schedule. For example, engine speed (ω_{eng}) stayed at or above a minimum of 1000 rpm, the given idle speed, and even in the most aggressive schedule (US06) it never exceeded its maximum rated speed of 4014 rpm. The brake specific fuel consumption (BSFC) at the typical idle speed of 1000 rpm was somewhat high, as shown in Table 2, reproduced below from Alothman (2023) with some values rounded to have less digits:

Table 2

Power (kW)	Speed (rpm)	BSFC (g/kWh)
7.66	1009	500
12.77	1183	400
24.64	1589	320
35.77	1937	285
47.63	2318	265
57.30	2613	255
77.74	3371	255
82.85	3685	265
85.58	4014	285

However, while BSFC is relatively high at engine idle speed, note that it gives fuel consumption *per kilowatt-hour.* This means that the absolute amount of fuel consumed was quite small, as very little power was actually drawn from the engine while idling. Since this vehicle has a CVT (see Figure 1), it was able to operate at optimal BSFC for any given engine speed.

One interesting result from this study is that the SOC ended up above 0.50 for all drive schedules. In fact, if the simulation is allowed to run through a schedule that uses aggressive regenerative braking (e.g. US06) multiple times in succession, the ESS can end up charged well into the uppermost quarter of its capacity by the end. While this is probably realistic, assuming a fairly simple ESS controller, it also indicates that a more sophisticated power management scheme may be wise. A controller that has a lower threshold for using electric launch and boost as SOC grows higher may provide an elegant solution to this problem, and that could be an interesting topic for future studies.

Appendix

The following initialization script is reproduced from here from Alothman (2023) for convenience only; no alterations were made from the original.

```
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 ;
```

The following function is called “fcn” in the Simulink model and is reproduced here from Alothman (2023) for convenience only; no alterations were made from the original.

```
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
```

References

Alothman, Maryam. 2023. "ECE 51018 Project 1 Instructions."

Mi, Chris, and M. Abul Masrur. 2017. *Hybrid Electric Vehicles: Principles and Applications with Practical Perspectives*. 2nd ed. Wiley. https://doi.org/10.1002/9781118970553.

United States EPA. 2022. "Dynamometer Drive Schedules." Web. https://www.epa.gov/vehicle-and-fuel-emissions-testing/dynamometer-drive-schedules.