

The primary objective of the first project is to analyze the performance of a *parallel* hybrid gas/electric vehicle. In this vehicle, an electric machine is to propel the vehicle at low speeds with the main engine disengaged. The electric machine is also used as a boost motor to improve high-speed accelerating characteristics. This permits a smaller internal combustion engine to be used without sacrificing overall performance. A block diagram of the vehicle drivetrain is depicted in Fig. 1. Relevant parameters are summarized in Table 1.

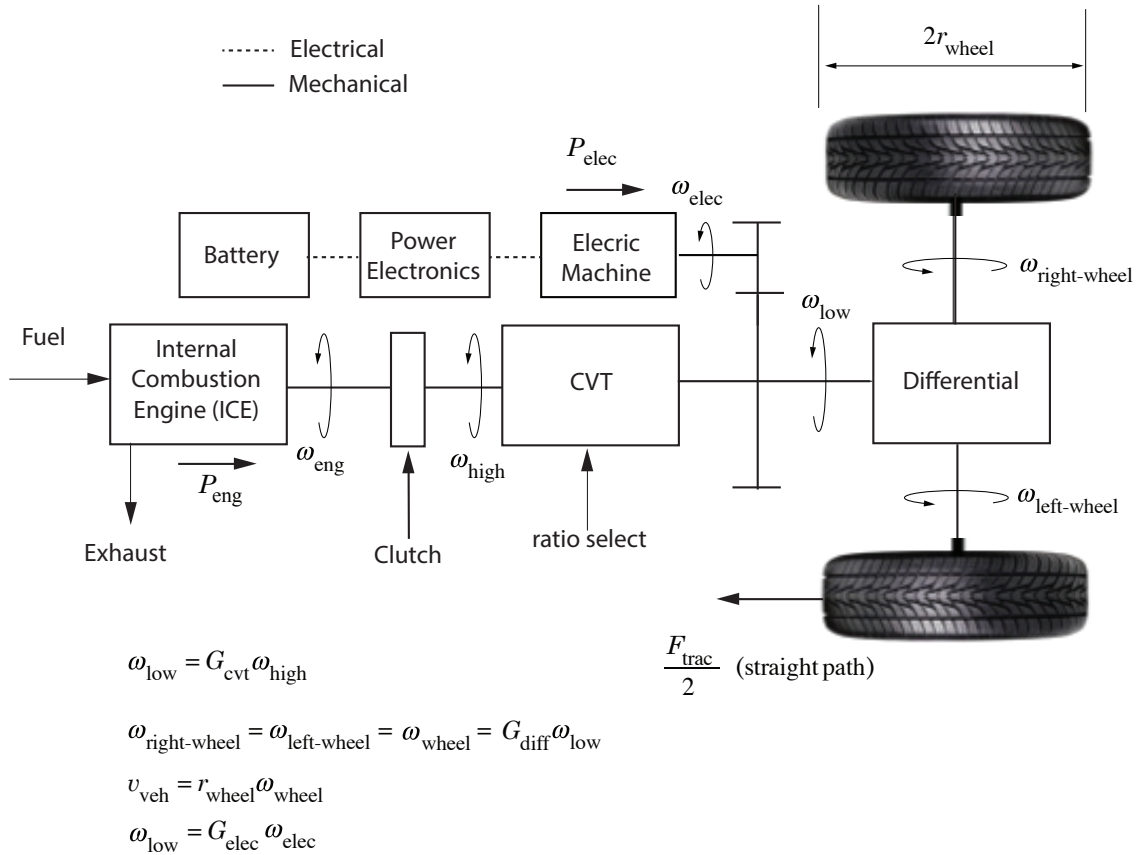


Figure 1: Mild parallel hybrid vehicle.

In order to analyze this architecture, you are to develop a Simulink<sup>TM</sup> model that accepts the driving schedule as an input and calculates the power, torque, and speed of the engine and motor, as well as the battery state of charge (SOC) and fuel usage. A top-level simulation block diagram is depicted in Fig. 2. The engine is to be operated along its optimum brake-specific-fuel-consumption (BSFC) characteristic, shown in Fig. 3. For convenience, these data have been digitized and are summarized in Table 2. In this project, we will use a simplified model of the battery and associated power electronics. This combination will be referred to as the energy storage subsystem (ESS). The energy storage capacity should be sufficient so that its SOC never exceeds 0.8 or falls below 0.2. The target SOC is 0.5. Adjust the overall mass of the vehicle to include the mass of the selected battery pack. Assume a gravimetric energy density of 46 Wh/kg. Also, be sure to include your own mass as the driver of the vehicle.

Table 1: Vehicle parameters

| Parameter                                       | Symbol                     | Value               |
|---|----------------------------|---------------------|
| vehicle mass w/o battery, passengers, or driver | $M_{\text{veh}}$           | 1746 kg             |
| wheel radius                                    | $r_{\text{wheel}}$         | 0.2794 m            |
| electric machine gear ratio                     | $G_{\text{elec}}$          | 1                   |
| transmission gear ratio (min)                   | $G_{\text{cvt,min}}$       | 0.5                 |
| transmission gear ratio (max)                   | $G_{\text{cvt,max}}$       | TBD                 |
| differential gear ratio                         | $G_{\text{diff}}$          | 0.268               |
| rolling resistance coefficient                  | $C_0$                      | 0.015               |
| aerodynamic drag coefficient                    | $C_D$                      | 0.35                |
| frontal area                                    | $A_F$                      | 1.93 m <sup>2</sup> |
| energy storage subsystem capacity               | $E_{\text{ess}}$           | 2 kWh               |
| energy storage subsystem round-trip efficiency  | $\eta_{\text{ess}}$        | 0.8                 |
| minimum engine speed                            | $\omega_{\text{eng,min}}$  | 1000 rpm            |
| minimum engine power                            | $P_{\text{eng,min}}$       | 10 kW               |
| maximum engine power                            | $P_{\text{eng,max}}$       | 85 kW               |
| initial SOC                                     | $\text{SOC}_{\text{init}}$ | 0.5                 |
| gravimetric density of gasoline                 | $m_{\text{gas}}$           | 0.75 kg/liter       |

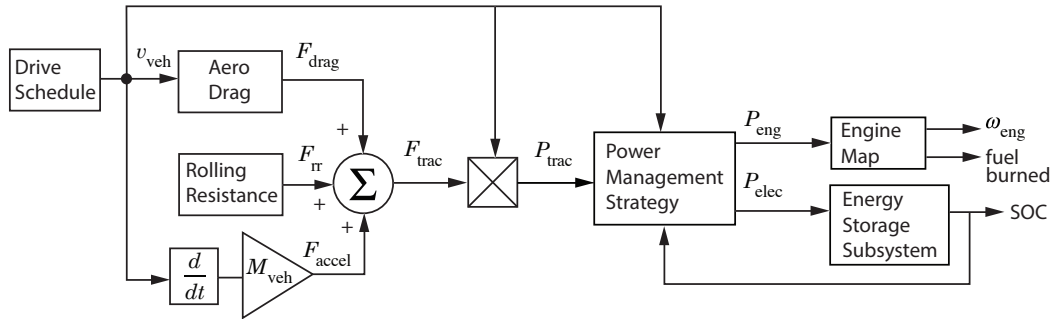


Figure 2: Top-level simulation block diagram.

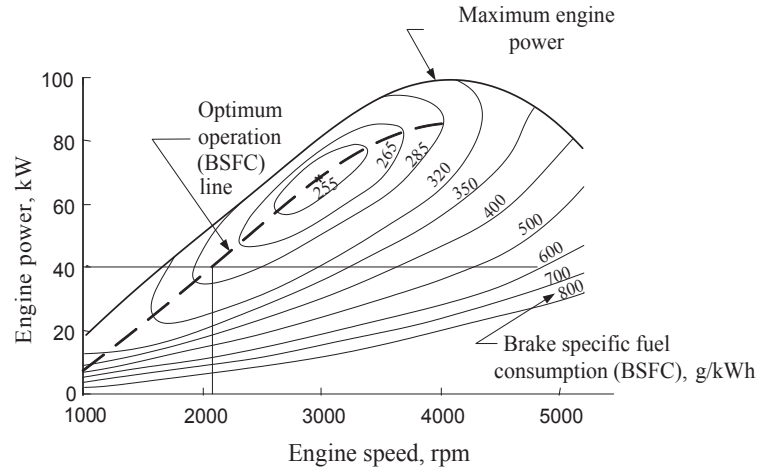


Figure 3: Engine map.

Table 2: Engine optimum speed and BSFC vs power

| Power (kW) | Speed (rpm) | BSFC (g/kW-hr) |
|------------|-------------|----------------|
| 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            |

### Power Management Strategy

Given the required net tractive power  $P_{\text{trac}}$ , 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, as opposed to providing a second power source to extend the vehicle range (this would make the vehicle a plug-in HEV or PHEV). Other operating strategies/constraints are listed below.

1. If the vehicle speed is below a threshold, the clutch is disengaged and the engine is shut off. The vehicle-speed threshold occurs when the CVT is operating at its lowest gear ratio  $G_{\text{cvt,min}}$  and  $\omega_{\text{eng}} = \omega_{\text{eng,min}}$ . In this mode of operation,  $P_{\text{eng}} = 0$  and  $P_{\text{trac}} = P_{\text{elec}}$ . This will be called electric launch mode.
2. If  $v_{\text{veh}} > v_{\text{veh,min}}$  and required  $P_{\text{trac}}$  is less than minimum engine power ( $P_{\text{eng,min}}$ ), the clutch is engaged but no fuel is provided to engine ( $P_{\text{eng}} = 0$ ). In this mode,  $P_{\text{elec}} = P_{\text{trac}}$ . A positive  $P_{\text{trac}}$  is supplied BY the electric machine (making it a motor) while a negative  $P_{\text{trac}}$  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 contrlled so that  $\omega_{\text{eng}} = \omega_{\text{eng,min}}$ . This will be called all-electric mode.
3. If  $P_{\text{trac}}$  is greater than maximum engine power along the optimum BSFC line (85 kW), assume  $P_{\text{eng}} = P_{\text{eng,max}}$ . In this mode,  $P_{\text{elec}} = P_{\text{trac}} - P_{\text{eng,max}}$ . This will be called electric boost mode.
4. Whenever  $v_{\text{veh}} > v_{\text{veh,min}}$  and  $P_{\text{eng,min}} < P_{\text{trac}} < P_{\text{eng,max}}$ , we will try to bring the SOC back to 0.5 by charging or discharging the battery at a rate of 4 kW. Initially, we will try using  $P_{\text{elec}} = 4000 \times \text{sign}(\text{SOC} - 0.5)$  and  $P_{\text{eng}} = P_{\text{trac}} - P_{\text{elec}}$ . If the calculated  $P_{\text{eng}}$  falls below  $P_{\text{eng,min}}$ , the clutch remains engaged; however, fuel is shut off ( $P_{\text{eng}} = 0$ ). In this case, the CVT ratio is controlled so that engine speed is  $\omega_{\text{eng,min}}$ . This will be called the charge-sustaining mode.

Whenever the engine is engaged and fueled ( $P_{\text{eng}} > 0$ ), its speed is assumed to be on the optimum BSFC line for the calculated power level. For the US EPA's published FTP75 (city), HWFET (highway) and LA92 (Los Angeles) driving schedules, calculate and plot the variables listed in Table 3. Also, plot the motor torque (N-m) versus its speed (rad/s).

For each drive cycle, calculate the total tractive energy ( $P_{\text{trac}}$  integrated with respect to time), the energy supplied by the engine ( $P_{\text{eng}}$  integrated with respect to time), and the energy supplied by

Table 3: Variables to be plotted

| Variable                | Symbol                 | Unit |
|-------------------------|------------------------|------|
| engine speed            | $\omega_{\text{eng}}$  | rpm  |
| engine power            | $P_{\text{eng}}$       | kW   |
| electric machine power  | $P_{\text{elec}}$      | kW   |
| electric machine speed  | $\omega_{\text{elec}}$ | rpm  |
| electric machine torque | $T_{\text{elec}}$      | N-m  |
| tractive force          | $F_{\text{trac}}$      | N    |
| tractive power          | $P_{\text{trac}}$      | kW   |
| battery state of charge | SOC                    | -    |

the ESS ( $P_{\text{elec}}$  integrated with respect to time), the energy lost to aerodynamic drag, the energy lost to the ESS, and the energy lost to rolling resistance. Summarize in the form of a table. Calculate the total fuel used, the miles travelled, the average miles per gallon, and the SOC at the end of the drive cycle. Summarize in the form of a table. Note: to get a converged value for mpg, you will need to repeat the drive cycles numerous times.

Grading will be based upon the following criteria: supporting analysis, documentation of computer models, correctness (plausibility) of results, and discussion of results.

For supporting analysis, calculate the tractive power and corresponding mpg assuming the vehicle is traveling at a steady 60 mph. This can be done using a calculator or Matlab. Compare these values to those established using the Simulink model with  $v_{\text{veh}}$  set to 60 mpg. How much of the tractive power is attributed to rolling resistance? How much of the tractive power is attributed to aerodynamic drag?

Documentation should be sufficient to allow someone else to duplicate all of the results based upon information in your report. This can be in the form of tables, figures, and/or text. Documentation should also include the initialization script, screenshots of pertinent Simulink windows, and Matlab codes used in generating the results.

For the results, each plot (figure) should be labelled and numbered. For the discussion, each figure should include a discussion to describe its content and any conclusions derived therefrom. Discussion points could include: does the engine speed stay within reasonable limits, (2) at what power level does the engine operate at most of the time, what is the bsfc at this power level, (3) how much does the SOC deviate from its target, ...

### **Bonus credit:** (1-3 points)

Other discussion points might include (1) how round-trip efficiency of the ESS affects mpg, (2) how the storage capacity of the ESS affects mpg, (3) how the number of passengers or cargo weight affects mpg, (4) how the charge/discharge rate affects mpg. Each of these would require additional runs to be made. You do not have to include the associated time-domain plots in the report (only the final numbers).

Based upon the results obtained for the given parameters and conditions, suggest changes that might improve the fuel efficiency. Implement your changes for one of the drive cycles. Options include modifying the power management strategy, increasing or decreasing ESS capacity, and/or downsizing the engine.

Reports should be typewritten. You may use any word processor that produces a pdf file. You will upload only the pdf file to Brightspace. Please review Syllabus for cheating policy. A plagiarism checker will be used. Late reports will be accepted if an extension is requested prior to due date. The request must state reason and promised submission date. Otherwise, 1 point per lecture that occurs following due date will be subtracted from graded report.