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 vehicle parameters and physical constants are summarized in Table 1.

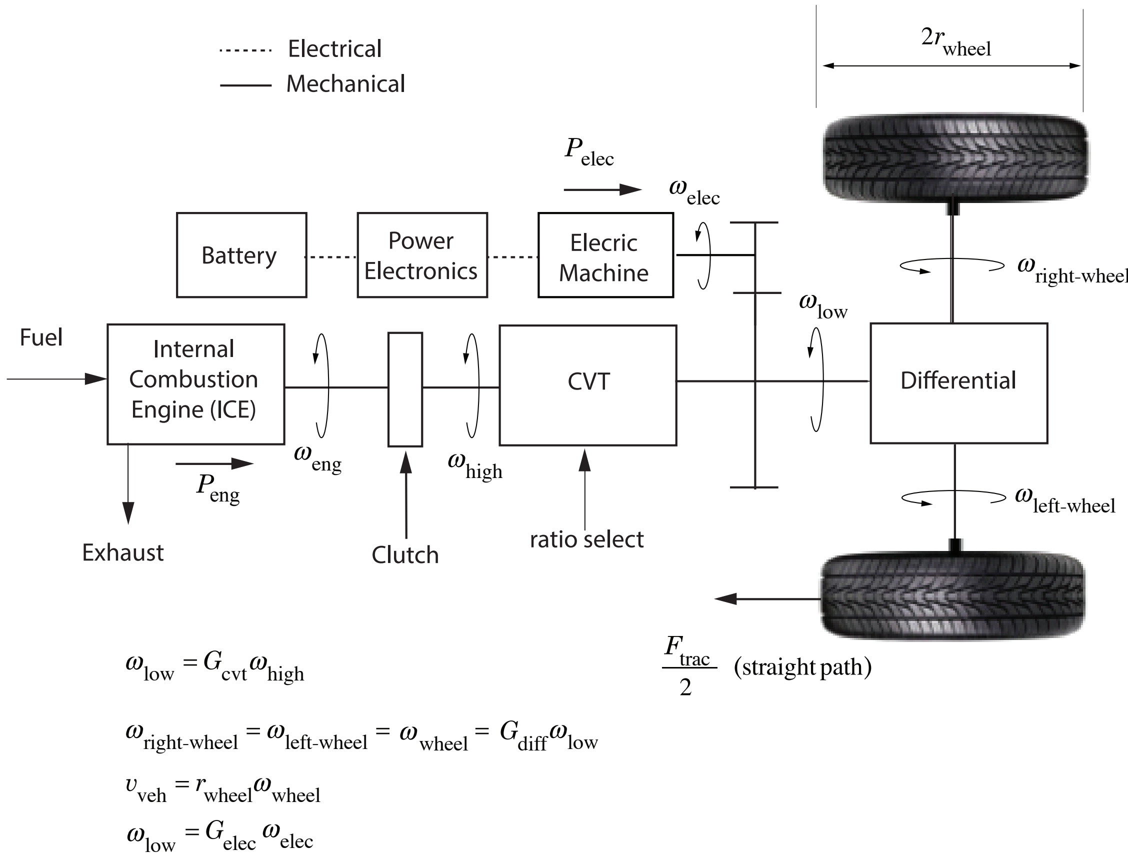

Figure 1: Parallel hybrid vehicle.

In order to analyze this architecture, you are to develop a Simulink™ model that accepts the drive 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 consumption. 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. We will adjust the overall mass of the vehicle to include the mass of the selected battery pack. Assume a battery mass density of 25 kg/kWh and an initial pack rating of 2 kWh. Also, assume a driver and passenger mass of 180 kg.

Table 1: Vehicle parameters

Parameter	Symbol	Value
vehicle mass w/o battery, passengers, or driver	M_{veh}	1746 kg
driver and passenger mass	$M_{\mathrm{passengers}}$	180 kg
wheel radius	r_{wheel}	0.2794 m
electric machine gear ratio	G_{elec}	1
transmission gear ratio (min)	$G_{\mathrm{cvt,min}}$	0.5
transmission gear ratio (max)	$G_{\mathrm{cvt,max}}$	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	$\omega_{\mathrm{eng,min}}$	1000 rpm
minimum engine power	$P_{\mathrm{eng,min}}$	5 kW
maximum engine power	$P_{\mathrm{eng,max}}$	85 kW
initial SOC	$\mathrm{SOC}_{\mathrm{init}}$	0.5
target SOC	$\mathrm{SOC}_{\mathrm{target}}$	0.5
maximum SOC	$\mathrm{SOC}_{\mathrm{max}}$	0.8
minimum SOC	$\mathrm{SOC}_{\mathrm{min}}$	0.2
mass density of gasoline	m_{gas}	0.75 kg/liter
mass density of ESS	m_{ess}	25 kg/kWh

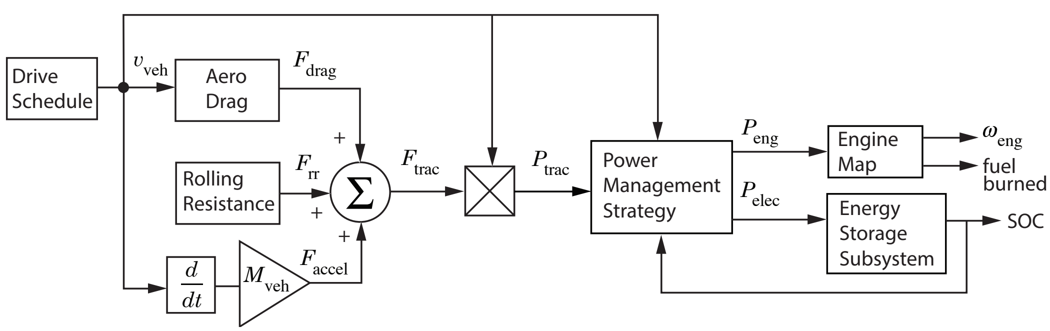

Figure 2: Top-level simulation block diagram.

Power Management Strategy

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, 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 idling. The vehicle-speed threshold occurs when the CVT is operating at its lowest gear ratio $G_{\mathrm{cvt,min}}$

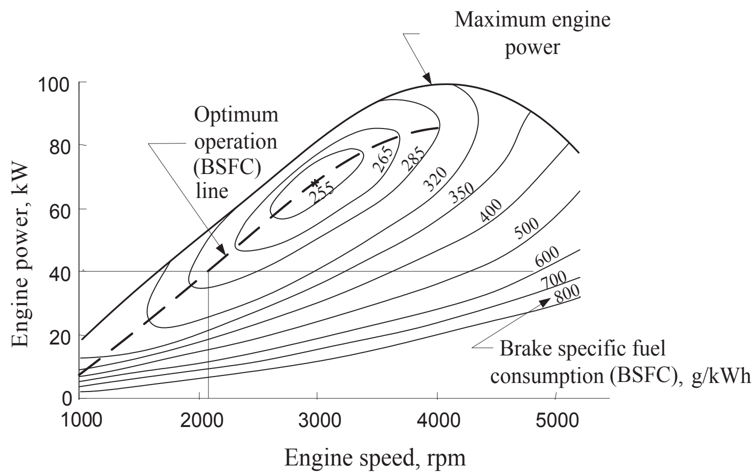

Figure 3: Engine map.

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

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_{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_{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 contrlled so that $\omega_{\text{eng}} = \omega_{\text{eng,min}}$. This will be called all-electric mode.

3. If P_{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 ESS. 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_{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 UDDS (city), HWFET (highway) and US06 (aggressive highway) driving schedules, calculate and plot the variables listed in Table 3. Also, plot the motor torque (N-m) versus its speed (rad/s). Note that the duration of each drive schedule is different. Therefore, you will need to adjust the simulation stop time accordingly.

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	-

For each drive cycle, calculate the total tractive energy (P_{trac} integrated with respect to time), the energy supplied by the engine (P_{eng} integrated with respect to time), and the energy supplied by the ESS (P_{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 results 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 set the simulation stop time much larger than the duration of one cycle (so as to capture multiple cycles).

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, provide a "first-law-of-thermodynamics" check of the results for each drive schedule. The net energy supplied by the engine and ESS should equal the sum of losses (aero, rolling resistance) plus the difference in kinetic energies at the finish and start of the drive schedule.

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: (1-2 points)

Suppose the engine is eliminated altogether and the ESS capacity (E_{ess}) is increased to 60 kWh. Assume the initial SOC = 1. Determine the vehicle range in miles for each of the drive cycles studied assuming SOC is not to fall below 0.1. You will need to adjust the vehicle mass by subtracting 125 kg (approximate engine weight) and adding $M_{\text{ess}} = E_{\text{ess}} m_{\text{ess}}$ for the net weight of the ESS. Repeat for various values of E_{ess} (always adding the appropriate mass. Discuss how the value of E_{ess} affects range for the three drive cycles.

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.