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Hybrid Powertrain Final Report

Introduction

Climate change remains a significant threat to the environment and public health. According to the Environmental Protection Agency [1], since the pre-industrial revolution in 1750 greenhouse gas emissions are a major cause of the rise in global temperatures, with CO_2 emissions accounting for nearly 79.4% of the total US gross greenhouse gas emissions in 2021 (weighted by global warming potential). Among CO_2 sources, fossil fuel combustion is the leading contributor, primarily due to transportation at 37.9%. Light duty trucks contribute the most to CO_2 emissions within the transportation sector at 37.3%, followed by freight trucks and passenger vehicles at 23.3% and 20.8%, respectively. If the U.S. hopes to curb global warming, the reliance on fossil fuels within the automotive industry must be reduced.

Several options exist for reducing fossil fuel consumption for automobiles, each with their own merits. Improvements in electric motor and battery technologies have allowed for the electrification of cars as a source of power. Automotive engineers have explored varying degrees of electrification, from either fully-electric vehicle (FEV) to hybrid electric vehicle (HEV) as explained by Husain [2]. Fully electric vehicles benefit from zero operating emissions, but sacrifice range as energy capacity from batteries are limited. Additionally, barriers such as charging infrastructure and raw material availability have restricted widespread adoption of FEV. Alternatively, hybrid vehicles can utilize redundant energy sources from both gasoline and electricity by having both an internal combustion engine (ICE) and electric motor. Hybridizing vehicles allows for improvements in fuel economy versus a single ICE since engine demand can be optimized by leveraging the efficiency of electric motors. HEV do not experience the shortfalls as with FEV since a smaller battery and electric electric motor are used, which allow for charging and power generation to be done with the ICE. For this reason, HEV may be the most feasible solution to curb the rise in global temperatures, at least in the near future.

As with any endeavor, an accurate model of a concept must be developed to set realistic expectations and optimize designs to reduce the number of iterations needed to be tested. A hybrid powertrain model of a medium duty truck was developed to predict and optimize the fuel economy based on a prescribed drive cycle. A 14,000 lb gross weight UHAUL truck with an ICE and electric motor was simulated in MATLAB Simulink. A vehicle longitudinal model was used to determine the power demand during an suburban driving cycle. An equivalent consumption minimization strategy (ECMS) was used to optimize the power split between the engine and motor based on the fuel efficiency. The PID controller of tracking the error between the reference value and actual value was used to follow the target power usage.

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Modeling

Vehicle longitudinal model

A vehicle longitudinal model is a mathematical representation of a vehicle's forward motion that takes into account various factors such as friction, air drag, and road profile. In this project, the vehicle longitudinal model has been simplified by neglecting the gear ratio and grade resistances and treating the road as a flat surface. The model only considers the vehicle rolling resistance and air drag resistance, with the governing equation shown in equation 1. To facilitate tracking the mechanical power demand, conservation of power has been implemented in this project (the conversion of electrical to mechanical power was neglected). This is because the power input to the system is equivalent to the power output when heat loss is ignored, as shown in equation 2.

The vehicle longitudinal model takes the driving cycle as its input. For testing purposes, a suburban driving cycle was selected, covering a velocity range of 0 to 60 MPH. The output of the model is the power demand required to drive the vehicle. When deceleration occurs, the model treats it as regenerative braking to simplify the power tracking process. If the power output is positive, it is distributed between the engine and battery model based on a lookup table in the ECMS, which determines the percentage of power allocated to each component.

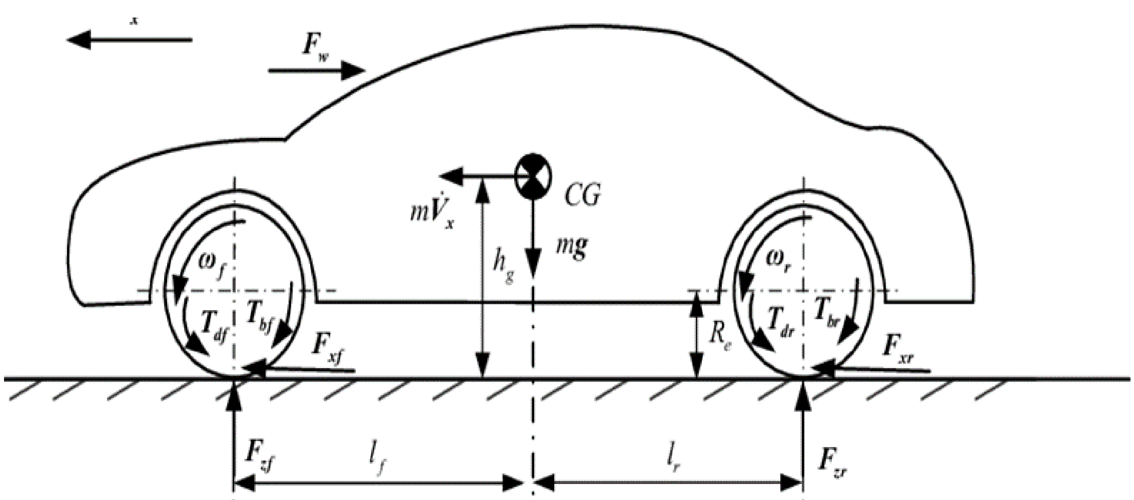

Figure 1: Vehicle longitudinal model

$$F_v - F_{Rr} - F_{Gr} - F_{Ad} = ma \quad (1)$$

$$V_C(F_v - F_{Rr} - F_{Gr} - F_{Ad}) = maV_c \quad (2)$$

Battery model

Obtaining a battery model is challenging due to the complex electrochemical nature and strong non-linear behavior of batteries. However, Xu's study [3] provides a feasible solution by representing the battery model in an equivalent circuit, as shown in Figure 2. The circuit comprises a voltage source (Eo(z)), a resistor (R1), and a parallel capacitor (C2) and resistor (R2). The voltage source is a function of the state of charge (SOC), denoted by z. Based on this equivalent circuit and derived state space matrix, a simulation model is constructed, as shown in Figure 4. Additionally, a look-up table is built to establish the relationship between SOC and the battery's output voltage (OCV) to construct the battery model. When the battery supplies power, it is necessary to calculate the percentage of state of charge (SOC) consumed. The equation for calculating SOC consumption is defined in equation 3. The resulting number is then subtracted from the initial state of charge to observe the change in SOC.

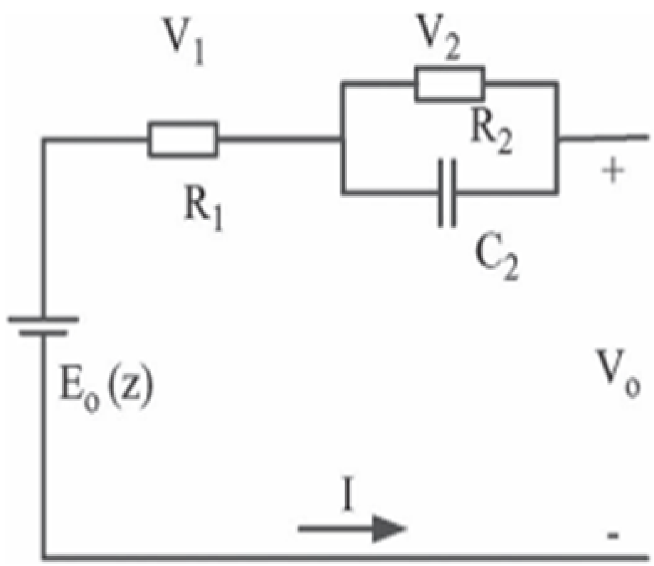

Figure 2: Battery equivalent circuit model

$$A = \begin{bmatrix} \frac{1}{-R_2 C_2} & 0 \\ 0 & 0 \end{bmatrix} \quad \mathrm{B} = \begin{bmatrix} \frac{1}{C_2} \\ \frac{\eta_i}{C_n} \end{bmatrix}$$

$$\mathrm{C} = \begin{bmatrix} 1 & a_i \end{bmatrix} \quad \mathrm{D} = R_1$$

Figure 3 The state space of battery equivalent circuit model

$$\frac{1}{Q_{max}} \int_0^t dq \tag{3}$$

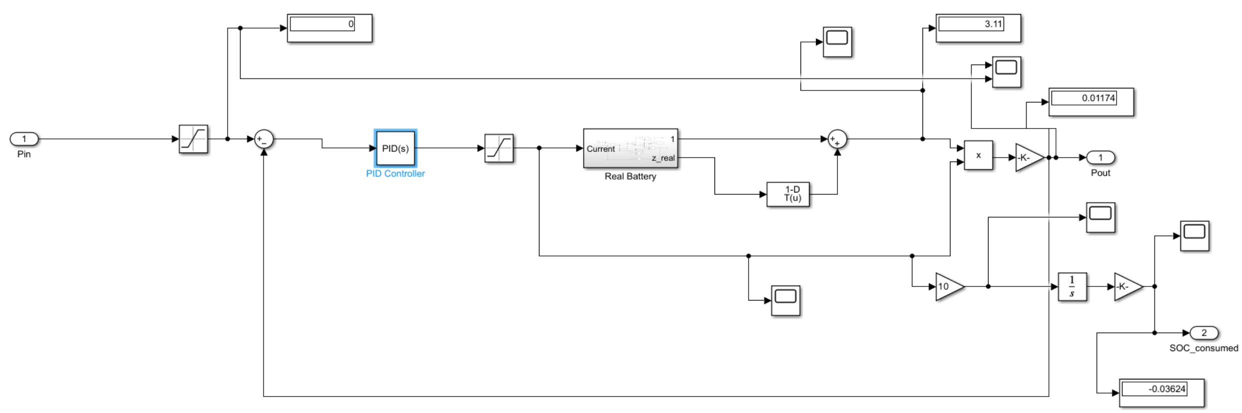

Figure 4: Battery equivalent circuit model in Simulink

Regenerative braking model
The regenerative braking system is designed to recapture some of the kinetic energy lost during braking and store it as electrical energy in the battery. When the brake is applied, the system converts the kinetic energy into electrical energy. In this model, negative power is an indication that the driver has applied the brake. Therefore, the regenerative braking model only considers the negative power and calculates the motor torque by dividing the power by the current motor speed. Two weight factors, which range from 0 to 1 and are determined by the state of charge (SOC) and wheel speed, are introduced to limit the charging speed. Once the motor torque is calculated, it is converted into motor power, which is then multiplied by 3600 seconds and divided by the battery capacity to determine the SOC charge rate through the regenerative

braking model. The initial SOC will be augmented by the SOC charge rate to determine whether the battery is being charged by the regenerative braking system.

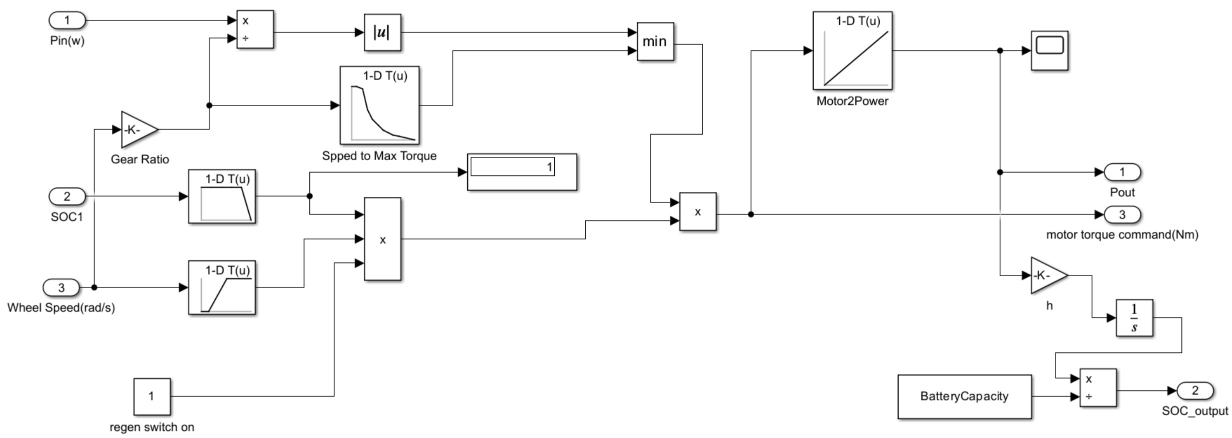

Figure 5: Regenerative braking model in Simulink.

Control Design

Servo-loop controllers

The controller is implemented in two places as reference value tracking, the goal is to make the error converge to zero. The error is calculated by subtracting the demand power to the actual power. The schematic is indicated in figure 5. The PID controller is used for controller design, because for the engine model, it is based on a lookup table, in which the state equation is unavailable. Since PID controller doesn't require the physical state, so the PID is applied in this scenario. In the engine module, the input is the error between the power demand and actual power output. The output of the PID control is the throttle of tuning the engine torque. The proportional, integral and derivative gains are 5, 1, and 1, respectively. Another PID controller is implemented at the battery model, the purpose is tracking the input value as well. The LQR is also the solution of designing the controller, since the state space of the battery model is given. Due to the simplicity, the same logic of PID design is implemented, and the proportional, integral and derivative gains are 20, 1 and 0, respectively.

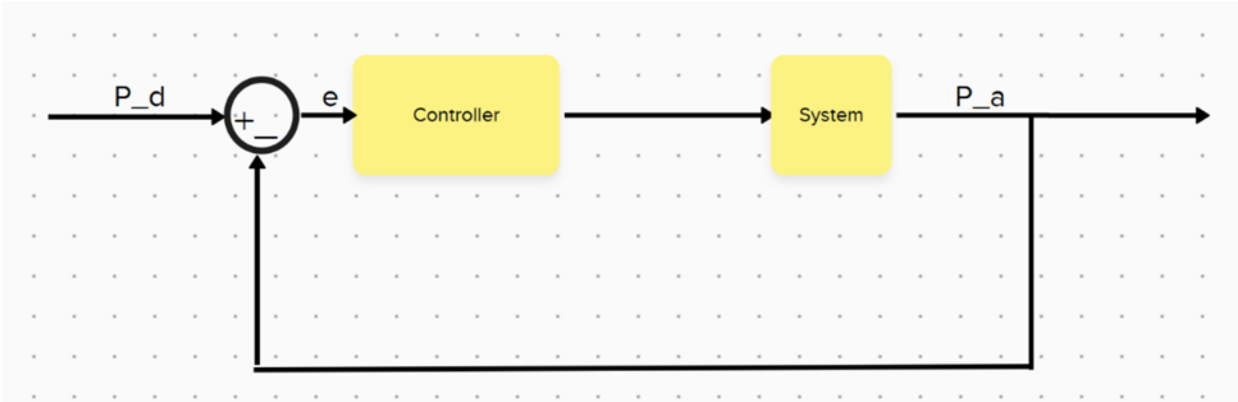

Figure 6: The schematic of PID controller

Supervisory controllers

An equivalent consumption minimization strategy (ECMS) was used to optimize the power split between the ICE and battery for reducing the fuel consumption of the powertrain. The ECMS model is a real-time optimization based on the operating state of the vehicle. The required engine and battery powers are determined based on a 3D look-up table of the total power demanded, shaft speed, and battery state of charge (SOC). The look-up table was generated remotely at several power demands, shaft speeds and SOCs. The objective function to be optimized is the fuel consumption $\dot{m}_{fequiv}$ in g/s, where $\dot{m}_{eng}$ is the engine fuel consumption, $\dot{m}_{batt}$ is the battery fuel consumption, and $f(SOC)$ is the penalty factor.

$$\dot{m}_{fequiv}(t) = \dot{m}_{eng}(t) + f(SOC)\, \dot{m}_{batt}(t) \tag{4}$$

$$f(SOC) = 1 - (1 - 0.7x_{SOC})x_{SOC}^{3} \tag{5}$$

$$x_{SOC} = \frac{SOC - \frac{SOC_L + SOC_H}{2}}{SOC_H - SOC_L} \tag{6}$$

The lower SOC limit SOC_L was assumed to be 0.2 and the upper limit SOC_H was 0.8. The engine fuel consumption is determined from testing, and given as a 2D lookup table based on torque and shaft speed. The battery fuel consumption is calculated based on the following equation:

$$\dot{m}_{batt}(t) = \frac{\bar{SC}_{eng} P_{batt}}{\eta_{electrical}} \tag{7}$$

where $\bar{SC}_{eng}$ is the average specific consumption of the engine from fuel to electrical energy, P_{batt} is the power demanded from the battery ($P_{batt} = P_{demand} - P_{eng}$), and $\eta_{electrical}$ is the efficiency including the inverter/controller and motor. The $\overline{SC}_{eng}$ is 0.5 for this study, and $\eta_{electrical}$ was determined via a 2D lookup table from motor torque and shaft speed. A lookup table was generated by iterating through power demands, shaft speeds and state of charges of $P_{demand} \in [0,\ 200]$ kW, $V_{shaft} \in [0,\ 2000]$ rpm, and $SOC \in [0,\ 1]$. The resulting optimum engine and motor powers are shown in Fig. 7.

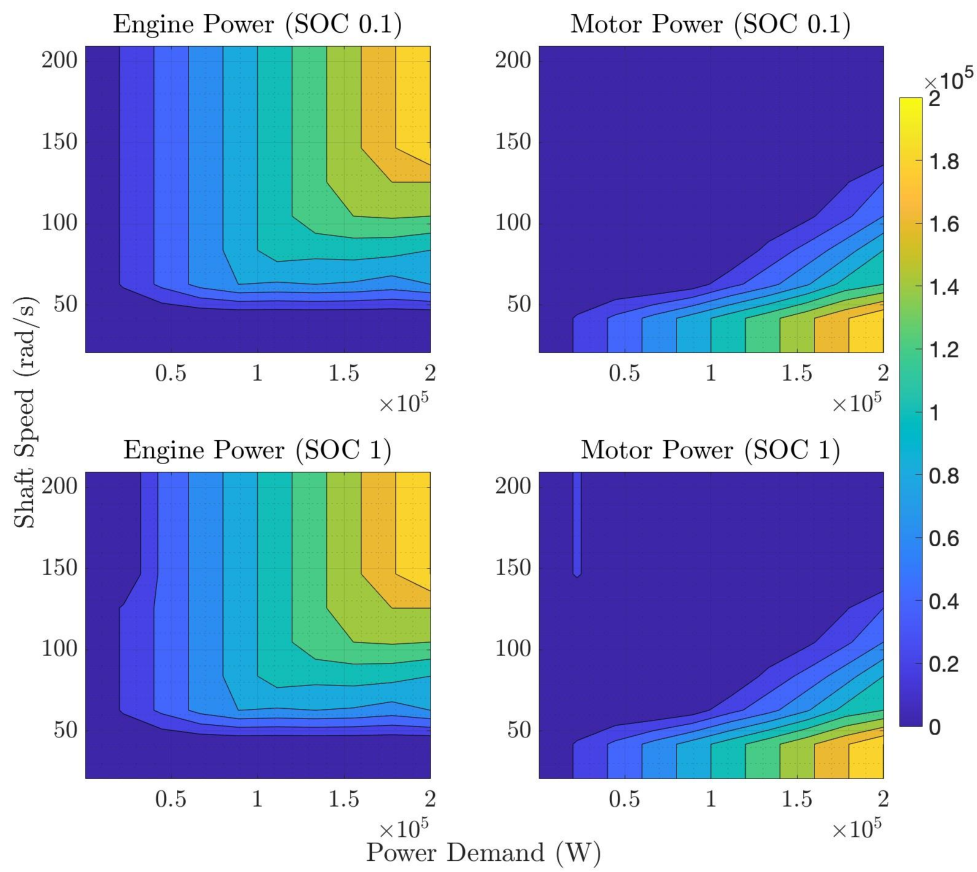

Figure 7: Optimum engine and motor powers at various SOCs, shaft speeds, and power demands.

Simulation Results

The simulation results are promising, showing that each component is functioning properly. In the power supply simulation, the power demand is equal to the sum of the battery power and engine power. The engine power is the major component that drives the vehicle, as the battery model defined in this project has a relatively small capacity of 1 kWh, which is significantly smaller than that of a regular hybrid vehicle. When the power demand is negative, the negative portion is directed to the regenerative braking system to convert the mechanical power into electrical power and store it in the battery. The battery SOC simulation shows that the battery starts at 0.6 SOC and experiences four rising points at times 130, 285, 635, and 745 seconds, which correspond to the huge spikes in the regenerative braking simulation. When there is a large negative power occurring, the driver presses the pedal to generate electricity power into the battery.

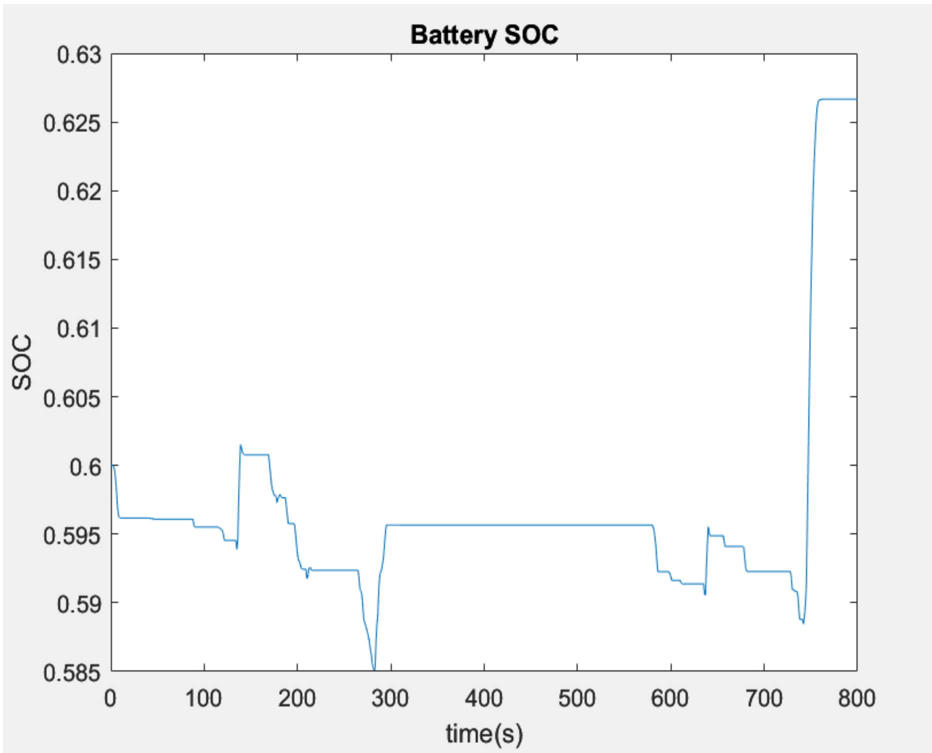

Figure 8: The change of SOC during driving cycle.

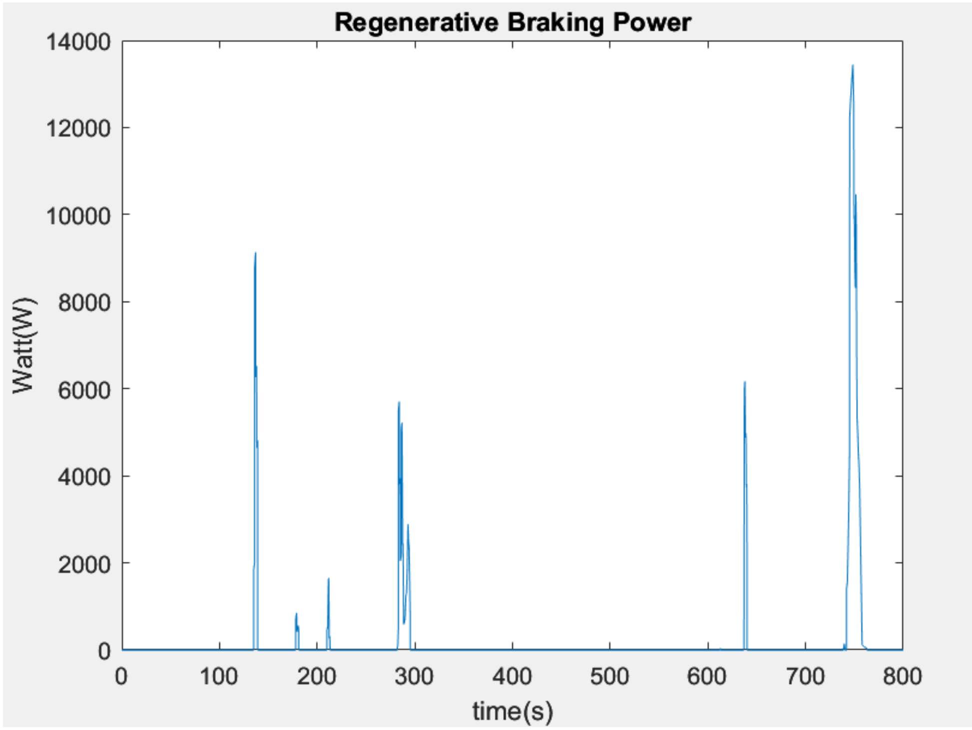

Figure 9: The power output of regenerative braking model.

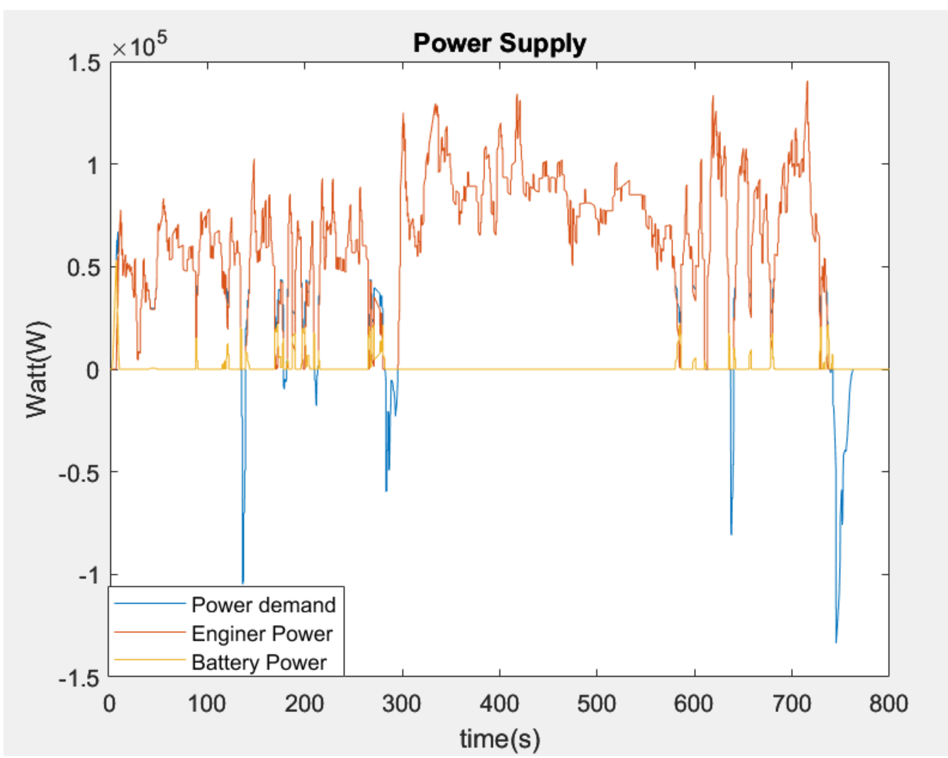

Figure 10: The vehicle power demand and power supply from the engine and battery model.

Conclusions

In conclusion, a hybrid vehicle powertrain model is a mathematical representation of a vehicle's powertrain system, which includes the engine, battery, motor, and other components that convert fuel energy into mechanical power to operate the vehicle. Powertrain models are essential in the design and optimization of powertrain systems for improved fuel efficiency, emissions reduction, and performance. A simulation approach is implemented in this project, to find the optimal fuel consumption using ECMS to find the power distribution into the engine and the battery, and the PID control for reference tracking. Rapid development in electrification and hybridization will reform the vehicle model and bring efficiency and performance to a higher level.

Appendix

Spec	UPS	UHAUL (20 ft)
Mass		
Curb weight	12,205 lb (5,540 kg)	7860 lb (3565 kg)
Fully loaded weight	18,205 lb (8262 kg)	14050 lb (6273 kg)
Tires		
Rolling radius	0.405 m	0.74 m (29.2 in)
Rolling resistance coeff.	0.006	0.01 (assumed)
Transmission		
Gear ratio	1	4.56
Efficiency	96 %	95.00%
Final drive		
Final drive ratio	4.78	1
Efficiency	97%	95.00%
Vehicle body		
Frontal area	6.25 m2	8.18 m2 (94.3 ft2)
Drag coefficient	0.7	0.7
Traction motor		**Ford 6.8l v10**
Peak power	200 kW	227 kW (305 hp) @ 4000 rpm
Peak torque	3000 Nm	569 Nm (420 ft-lb) @ 3000 rpm
Battery ESS		
Battery cell spec	LF105 cell	Duralast 65-EFB
Energy capacity (hybrid)	59.14 kWh	1008 Wh (12V*84Ah)*10
Fuel Cell		
Type	HyPM HD 30 kW	N/A

References

[1] The Environmental Protection Agency, “Inventory of U.S. Greenhouse Gas Emissions and Sinks,” April, 2023.

[2] Husain, “Electric and Hybrid Vehicles: Design Fundamentals,” CRC Press L, Chapter 1.

[3] Jun Xu, S. M. (2014). The State of Charge Estimation of Lithium-Ion Batteries Based on a Proportional-Integral Observer. *IEEE*, 1-9.