

LEV 2024 Coursework

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Abstract

This report presents the modeling and analysis of a Series Hybrid Electric Vehicle powertrain system. It explores the dynamic behavior of motor, engine, generator, and battery power profiles under various driving conditions, such as acceleration, cruising, deceleration, and steady-state operation. The report also discusses the control strategies for optimizing gear ratios, managing the state of charge, and ensuring efficient energy use throughout different driving phases. The findings highlight key insights into the vehicle's energy efficiency and operational strategy.

Nomenclature

DC-DC Direct Current to Direct Current Converter

GearRatio Ratio of Input Torque to Output Torque in the Final Drive System

i Current (A)

P_i Proportional-Integral Controller (PI controller)

P_{battery} Battery Power (W)

P_{engine} Engine Power (W)

P_{generator} Generator Power (W)

P_{motor} Motor Power (W)

R Resistance (Ω)

RPM Revolutions Per Minute (engine speed)

SHEV Series Hybrid Electric Vehicle

SOC State of Charge (%)

SOC_{actual} Actual State of Charge for Battery (%)

SOC_{target} Target State of Charge for Battery (%)

t Time (seconds)

t_B Input Torque to the Final Drive System (Nm)

t_F Output Torque from the Final Drive System (Nm)

t_{actual} Actual Torque for the Generator (Nm)

t_{target} Target Torque for the Generator (Nm)

V Vehicle Speed (m/s)

V_{battery} Voltage of the Battery (V)

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1. Declaration

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2. Introduction

This report details the design, modeling, and control of a Series Hybrid Electric Vehicle (SHEV). It covers the vehicle's powertrain components, including the electric motor, engine, generator, and battery, analyzing their performance across different driving phases. The study aims to optimize the efficiency of the vehicle's energy management system and control strategies.

3. C1 - Research into Hydrogen Propulsion systems

3.1. Introduction

Hydrogen propulsion systems are promising alternatives for sustainable transportation, primarily because hydrogen, when used as fuel, emits only water vapour (5). The two primary technologies using hydrogen are hydrogen combustion engines (HCEs) and hydrogen fuel cells (HFCs). Each approach has operational principles, advantages, disadvantages, and requirements. This comparison will explore these two systems in detail.

3.2. Hydrogen Combustion Engines (HCEs)

3.2.1. Operational Principle

Hydrogen combustion engines operate similarly to traditional internal combustion engines (ICEs). Hydrogen, rather than petrol or diesel, is injected into the engine's cylinders, where it combines with oxygen and ignites. The explosion drives pistons, producing mechanical power (3).

HCEs require specific modifications for hydrogen fuel:

- Higher Compression Ratios: Hydrogen has low ignition energy, so engines need higher compression ratios to maximize efficiency (12).
- Better Cooling Systems: Hydrogen burns at a higher temperature than petrol, so HCEs require better cooling (13).
- Ignition Systems: Hydrogen's wide flammability range demands precise control, often achieved with direct fuel injection or improved spark systems (7).

3.2.2. Components and Sensor Technologies

Hydrogen combustion engines include components commonly found in ICEs but have adaptations:

- Fuel Injection System: To manage hydrogen's high flammability, direct or sequential port injection systems are used, often controlled by high-speed sensors (8). Port fuel injector shown in Fig. 1 and sequential injection system shown in Fig. 2
- Knock Sensors: These monitor combustion for premature ignition or "knocking," which hydrogen can exacerbate (2).
- Hydrogen Detection Sensors: Hydrogen leaks are hard to detect (it is colorless and odorless), sensitive hydrogen sensors are required for safety (10).

3.2.3. Advantages and Disadvantages

Advantages:

- Cost-Effectiveness: HCEs use many existing ICE components, simplifying manufacturing and reducing costs (6).
- Reduced Emissions: Hydrogen combustion emits primarily water vapor, though some nitrogen oxides

(NOx) can still be produced due to high temperatures (11).

- Familiarity: Mechanics are already familiar with ICE technology, making it easier to transition to hydrogen-based systems (3).

Disadvantages:

- Lower Efficiency: Hydrogen combustion is less efficient than hydrogen fuel cells because mechanical energy conversion has more inherent losses (9).
- NOx Emissions: Though zero CO_2 is produced, high combustion temperatures can generate NOx, necessitating exhaust treatment (13).
- Storage and Refueling Challenges: Hydrogen has a low energy density by volume, requiring high-pressure tanks for storage, which are bulky (8).

3.3. Hydrogen Fuel Cells (HFCs)

3.3.1. Operational Principle

Hydrogen fuel cells generate electricity directly through an electrochemical reaction rather than combustion. In an HFC, hydrogen gas enters the anode side of the cell, where it splits into protons and electrons. The protons pass through a membrane to the cathode side, while the electrons travel through an external circuit, creating an electric current (1). On the cathode side, oxygen from the air combines with the protons and electrons, producing water as the only emission.

The most common type of fuel cell used in vehicles is the Proton Exchange Membrane Fuel Cell (PEMFC), because it has a relatively low operating temperature (60–80°C) and quick start-up time (3).

3.3.2. Components and Sensor Technologies

Hydrogen fuel cells require complicated control systems to maintain safe and efficient operation:

- Membrane Electrode Assembly (MEA): The core of PEMFCs, where the electrochemical reaction occurs (9).
- Hydrogen and Oxygen Sensors: Monitor hydrogen and oxygen levels to keep the ideal stoichiometric ratio, allowing efficient energy production (11)
- Humidity Sensors: Essential to maintain membrane hydration, as dry membranes lose conductivity, reducing performance (12).
- Temperature Sensors: Monitor cell temperature to prevent overheating and ensure efficient operation (2).

3.3.3. Advantages and Disadvantages

Advantages:

- High Efficiency: Fuel cells are generally more efficient than combustion engines, especially at low loads (8)
- Zero Emissions: HFCs produce only water and heat, with no NOx emissions or other pollutants (1).

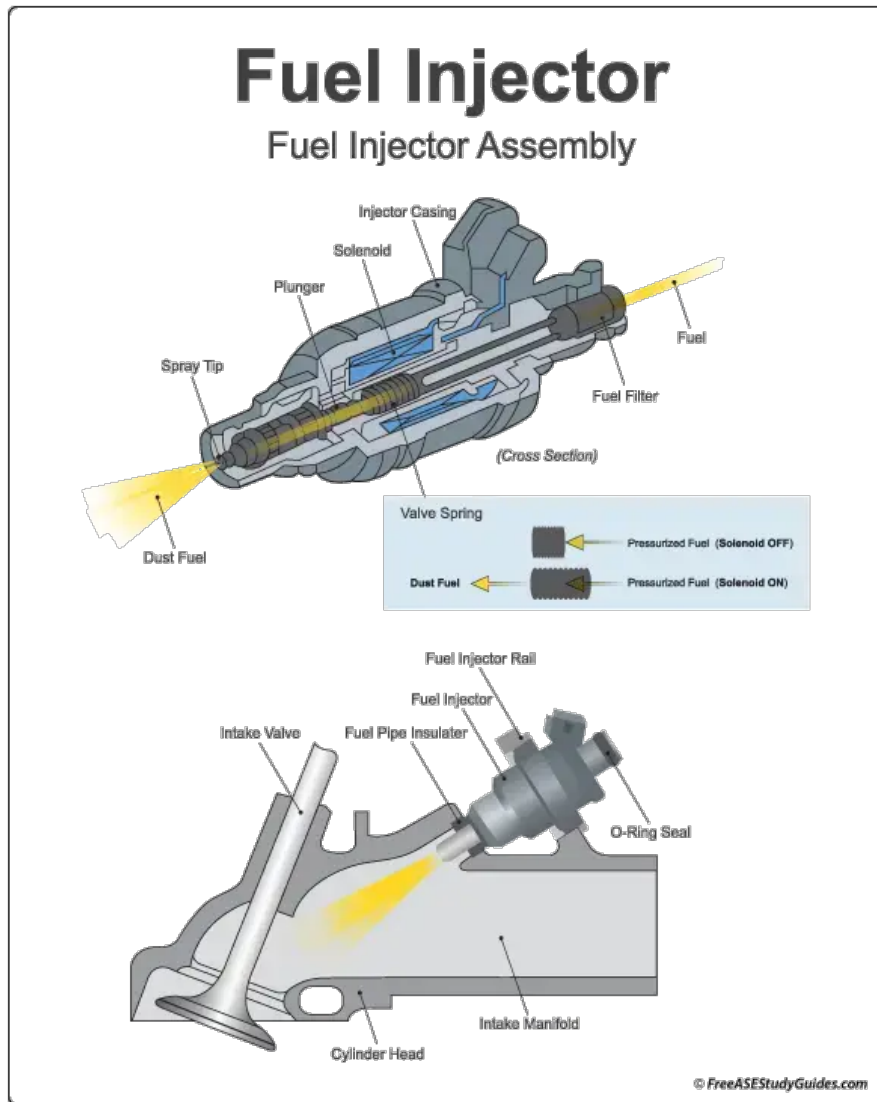


Fig. 1: Port Fuel Injector (4)

- Quiet Operation: Fuel cells operate quietly since there is no combustion involved (6).

Disadvantages:

- Cost and Complexity: Fuel cells are expensive to produce due to materials like platinum catalysts in the MEA, and require complex control systems (3).

- Durability Issues: Fuel cell performance can degrade over time, particularly if impurities in hydrogen or operating conditions affect the membrane (13).

- Storage and Infrastructure Challenges: Like HCEs, HFC systems require pressurized hydrogen tanks and infrastructure, which is still underdeveloped in many regions (11).

3.4. Future of Hydrogen Propulsion

Table 1 shows what was previously discussed. The conclusion is generally that HFC systems are better, but HCE systems are more achievable.

3.5. Future of Hydrogen Propulsion

Both hydrogen combustion engines and hydrogen fuel cells have potential roles in reducing carbon emissions in the transportation sector. HCEs may serve as a transitional technology due to lower upfront costs and compatibility with existing engine manufacturing. HFCs, on the other hand, offer superior efficiency and true zero-emission operation, making them ideal for long-term sustainability goals.

Ultimately, the choice between HCEs and HFCs

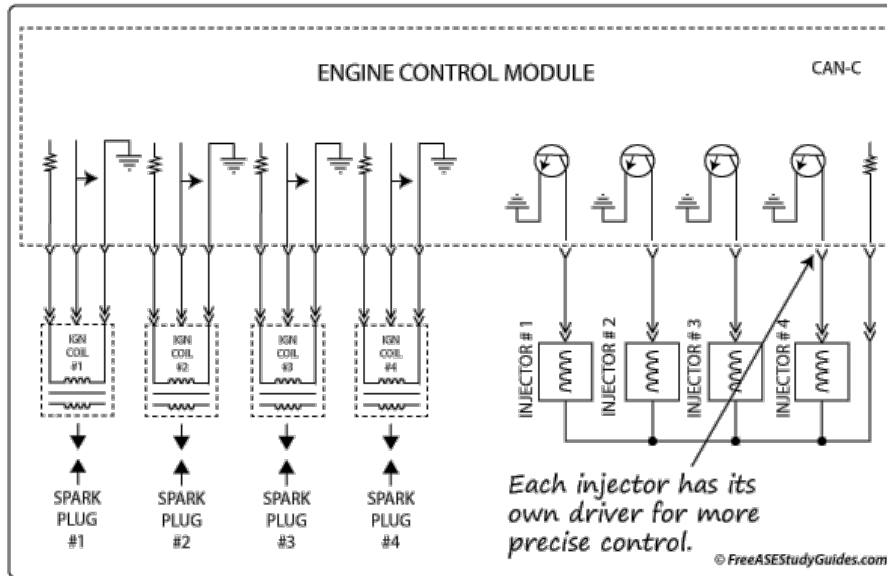


Fig. 2: Sequential Injection System (4)

Aspect	Hydrogen Combustion Engine (HCE)	Hydrogen Fuel Cell (HFC)
Design Philosophy	Adaptation of ICE technology to burn hydrogen	Electrochemical system for direct electricity generation
Primary Output	Mechanical power	Electrical power
Efficiency	Lower efficiency due to mechanical conversion losses	Higher efficiency from direct electrical output
Emissions	Water vapor, some NOx	Water vapor only
Operational Noise	Moderate (combustion noise)	Low (minimal moving parts)
Cost	Lower initial costs, scalable with ICE manufacturing tech	Higher costs, dependent on advanced materials

Table 1: Design Philosophy and Operational Differences

may depend on vehicle type and use case. For instance, HCEs could be used in heavy-duty applications where durability is crucial, while HFCs might be better suited for passenger vehicles that prioritize efficiency and emissions. Both systems, however, will rely heavily on advancements in hydrogen infrastructure to enable widespread adoption (3)(13) .

4. C2 - Design and Development: Series Hybrid Vehicle Sizing

Road requirements are listed in Appendix A of the project brief and also in Table 2.

4.1. Combustion Engine Selection

4.1.1. Lower Cost and Simpler Emissions Compliance

Gasoline engines are generally cheaper and simpler than diesel engines, which need costly, complex emissions controls like particulate filters to meet regulations (14)

4.1.2. Lower Noise and Vibration

Gasoline engines run more quietly and with less vibration, which enhances the driving experience, a key factor in passenger vehicle comfort (15)

Candidate Number	266720
Vehicle Mass	900kg
Area	1.8 m ²
CD	0.3
Tamb	27 C
Generator to motor net eff	79%
Battery to motor net eff	91%
Grid to Battery net eff	91%
Electricity price	0.52 £/kwh
Fuel price	1.48 £/L
Overall Gear Ratio	7
Gear Eff	95%
Gradient for	4
Grabbility degree	
Vehicle top speed	130 kph
Acceleration 0-100	7.2 s

Table 2: Appendix A from brief for candidate numbers ending in 0

4.2. Powertrain sizing

4.2.2. Electric Motor Speed and Torque Calculation

4.2.1. Power Calculation for Road Grade at 70 kph

Motor Speed ω_{motor}

Gravitational Force F_{grade}

$$F_{\text{grade}} = m \cdot g \cdot \sin(\theta), \quad (1a)$$

$$900 \cdot 9.81 \text{m/s}^2 \cdot \sin(4) = 615.9 \text{N}, \quad (1b)$$

$$\omega_{\text{motor}} = \frac{v}{r} \cdot G \quad (6a)$$

$$\frac{70,000}{60^2} \cdot 7 = 47.6 \text{rad/s}, \quad (6b)$$

Aerodynamic Drag Force F_{drag}

$$F_{\text{drag}} = \frac{1}{2} \cdot \rho \cdot C_D \cdot A \cdot v^2 \quad (2a)$$

$$\rho = \frac{m}{RT} = \frac{28.97}{8.31 \cdot 10^3 \cdot (27 + 273)} = 1.16 \quad (2b)$$

$$\frac{1}{2} \cdot 1.16 \cdot 0.3 \cdot 1.8 \cdot \frac{70 \cdot 1000}{60 \cdot 60} = 6.1 \text{N}, \quad (2c)$$

Motor Torque τ_{motor}

$$\tau_{\text{motor}} = \frac{F_{\text{total}} \cdot r}{G \cdot \eta_{\text{gear}}} \quad (7a)$$

$$\frac{615.9 \cdot 0.35}{7 \cdot 0.95} = 32.4 \text{Nm}, \quad (7b)$$

Rolling Resistance Force F_{rolling}

$$F_{\text{rolling}} = C_r \cdot m \cdot g, \quad (3a)$$

$$0.015 \cdot 900 \cdot 9.81 = 132.4 \text{N}, \quad (3b)$$

Total Force F_{total}

$$F_{\text{total}} = F_{\text{grade}} + F_{\text{drag}} + F_{\text{rolling}} \quad (4a)$$

$$615.9 + 6.1 + 132.4 = 754.4 \text{N}, \quad (4b)$$

Power Required P_{motor}

The required motor power at this speed is:

$$P_{\text{motor}} = F_{\text{total}} \cdot v \quad (5a)$$

$$754.4 \text{N} \cdot \frac{70 \cdot 1000}{60^2} = 14.56 \text{kW}, \quad (5b)$$

4.2.3. Engine Sizing

Required Power by the Engine

$$P_{\text{engine}} = \frac{16.9 \text{kW}}{2} = 8.45 \text{kW} \quad (8)$$

Fuel Efficiency (BSFC)

Optimal BSFC is shown in Appendix B of the brief and shown in Fig. 3.

This shows optimal bsfc is 222g/kWh.

Fuel Consumption Calculation

$$\dot{m}_{\text{fuel}} = \frac{100 \cdot P_{\text{engine}} \cdot BSFC}{v} \quad (9a)$$

$$\frac{100 \cdot 8.45 \cdot 222}{70000/60^2} = 9.65 \text{kg}, \quad (9b)$$

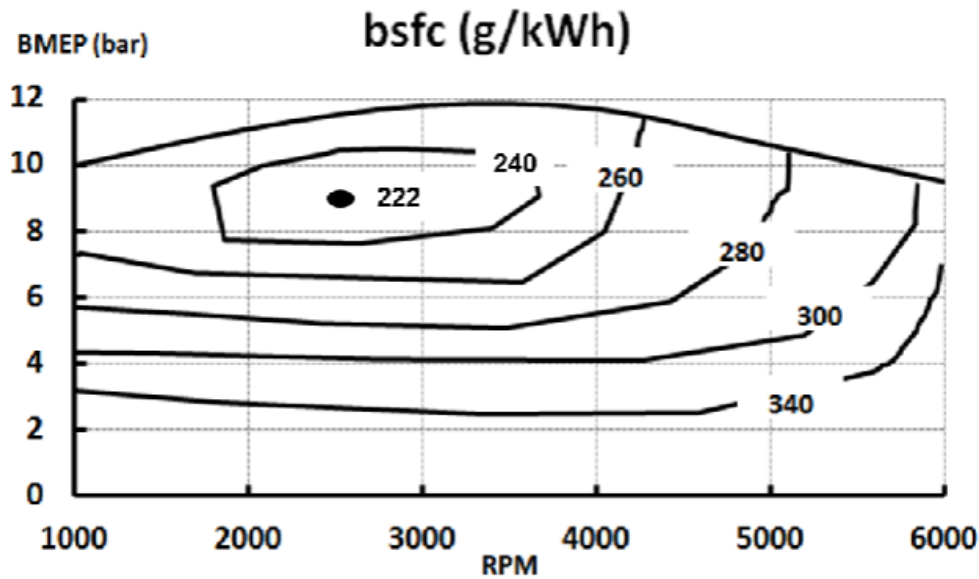


Fig. 3: BSFC

The average density of gasoline is approximately 0.745 kg/L (16).

$$\frac{9.65}{0.745} = 12.95L/h \quad (10)$$

4.2.4. Fuel Tank Size

The MATLAB code can be found in the appendix. In the code it gives the figures that are shown in Fig. 4, 5, 6, 7 and 8.

It loads WLTP Class 3 data, then calculates and plots speed and acceleration over time. Then it computes drag, rolling resistance (a constant), and acceleration forces. Plots these forces and calculates the resulting power and cumulative energy consumption over the cycle. Then using a 20 kWh battery, it calculates the maximum range on electric power alone. The remaining range required from the engine is determined by subtracting the EV range from the total 300 km journey. Based on the engine's Brake-Specific Fuel Consumption (BSFC) of 220 g/kWh, it calculates the total fuel required to support the remaining range, assuming no regenerative braking. Then it outputs fuel requirements and displays bar plots showing range distribution (EV vs. engine) and energy requirements for both battery and engine. It also includes efficiencies calculation.

The results are as follows:

Average energy consumption: 310.84 Wh/km

EV range (battery only): 64.34 km

Engine range needed: 235.66 km

Fuel required for 300 km: 28.63 liters

Therefore, a 30L fuel tank would be more than sufficient for 300km.

4.2.5. Alternative Hydrogen Fuel Cell size

An added hydrogen fuel cell section has now been added to the end of the code that is in the appendix. It takes into account efficiency and hydrogen energy density. It gives us a result of 29.05 liters.

5. Engine Control

5.1. Pseudocode for Engine Start Stop

Pseudocode flow chart has been placed in the appendix.

In the flow chart, upon start, there is a data gathering stage. There then is a question about whether a large amount of torque is required instantly. If so then the motor has to be on to deliver instant torque. Then temperature, power requirements, and state of charge is checked to see if the engine will be switched on. If none of trigger the engine, it will check to see if the motor should be on instead, and if not will go back to the gather data stage to restart the loop. If it does trigger the engine then it asks itself if the engine has been switched on and off a lot recently. If yes, it doesn't switch it on, to minimise driver disturbance.

If the engine is still triggered it will gather data again and start the same checks again. This time, however it checks for over heating last and will bypass the frequency check. This is because the engine overheating is serious. It also within this stage checks whether there is supplemental motor action needed for performance requirements.

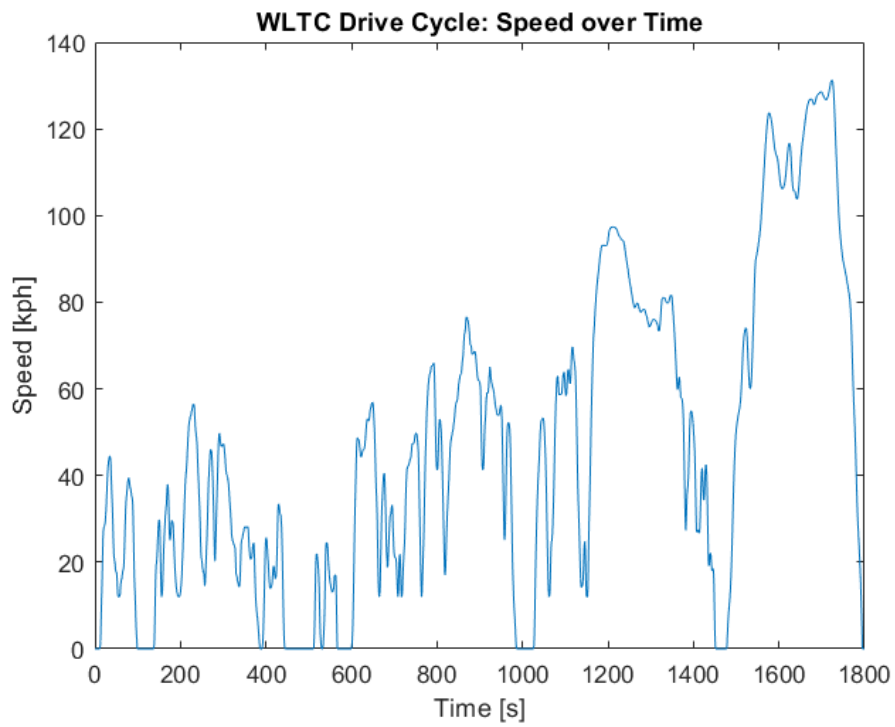


Fig. 4: WLTC Drive Cycle: Speed over Time

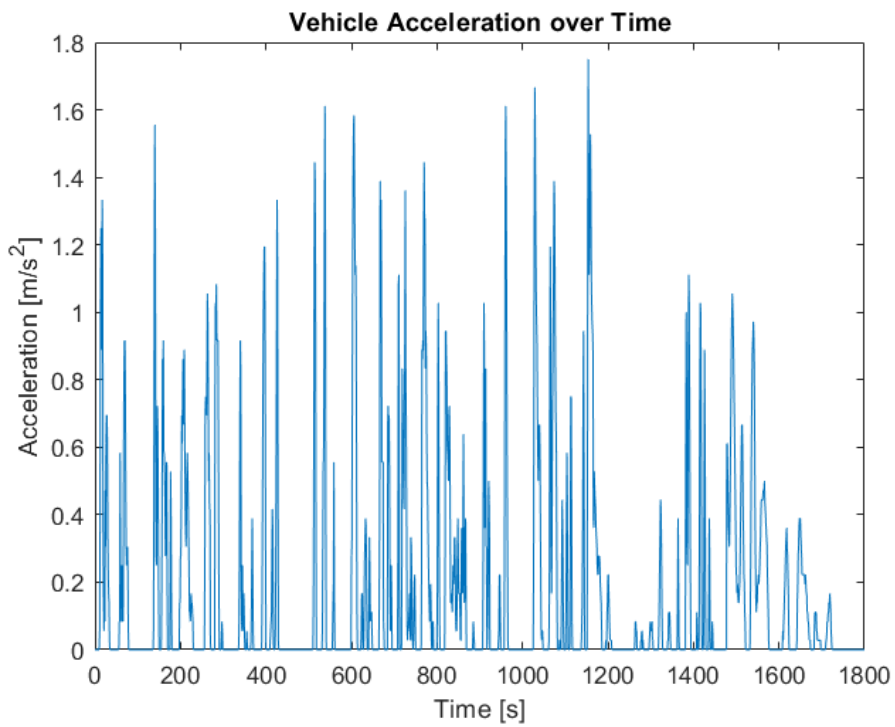


Fig. 5: Vehicle Acceleration over Time

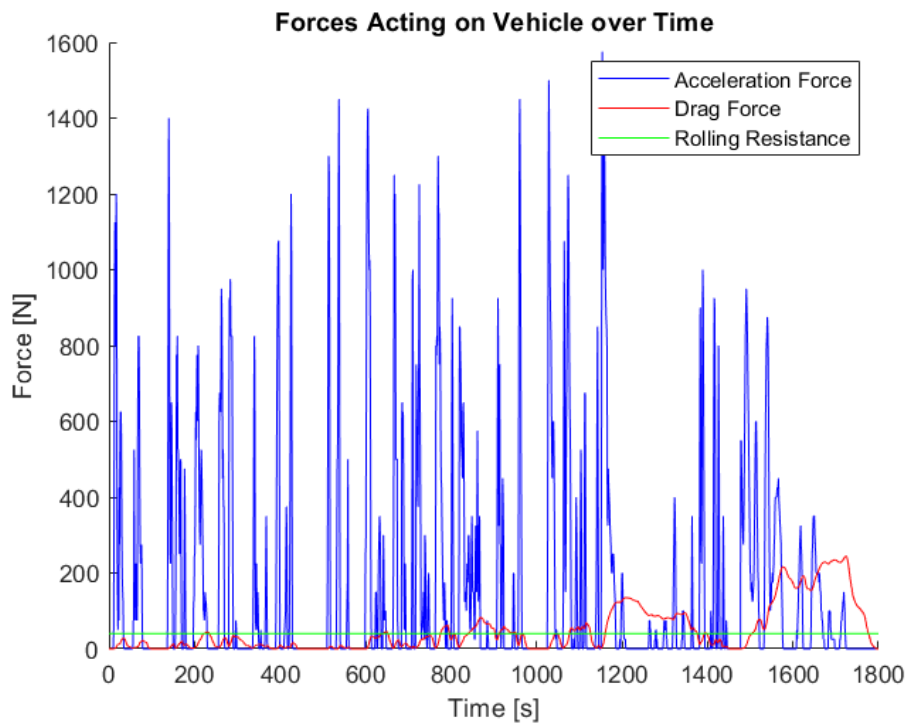


Fig. 6: BSFC

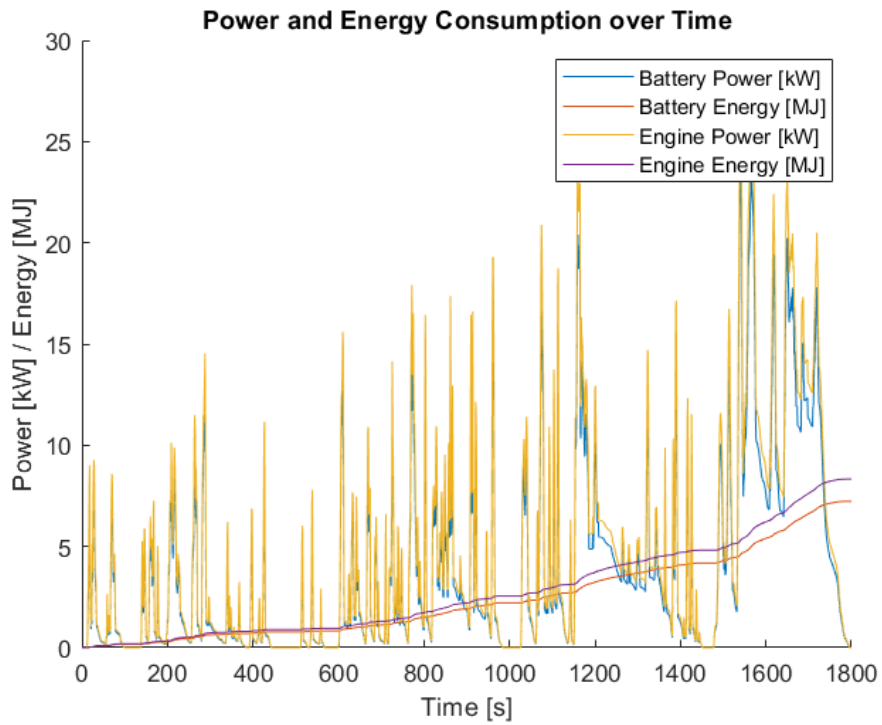


Fig. 7: Force Acting on Vehicle over Time

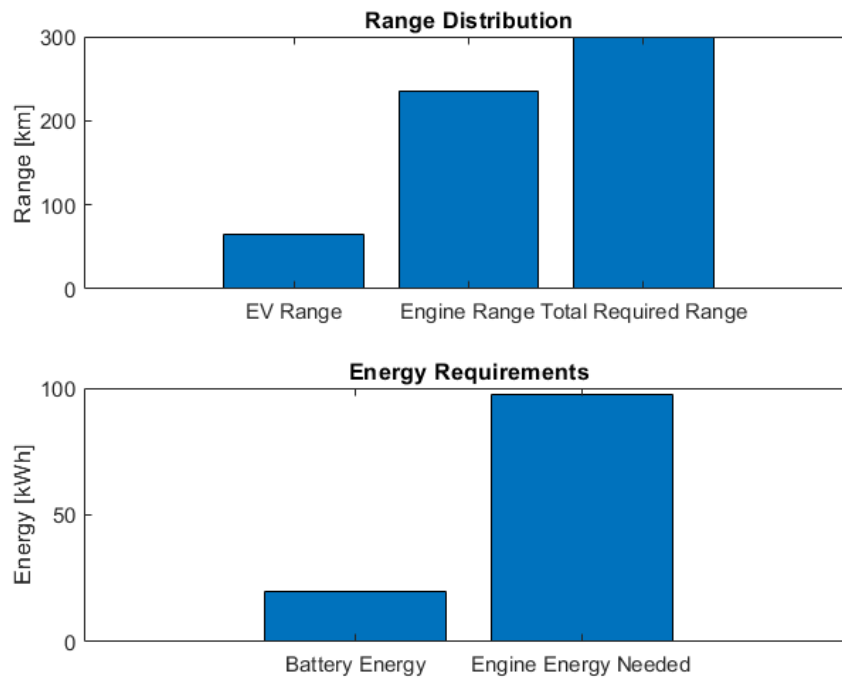


Fig. 8: BSFC

5.2. Cost Function

5.2.1. Define the Cost Function

Normalise Fuel Consumption and Emissions

- Collect data on fuel consumption and emissions (NOx, HC, and CO) across different engine speeds while the engine produces 10 kW.

- Normalise each parameter to a value between 0 and 1 by dividing by its maximum value across all speeds. This gives each factor a comparable scale, enabling us to create a single cost function.

$$Fuel_{norm} = \frac{FuelConsumption}{MaxFuelConsumption}, \quad (11a)$$

$$NOx_{norm} = \frac{NOxEmissions}{MaxNOxEmissions}, \quad (11b)$$

$$HC_{norm} = \frac{HCEmissions}{MaxHCEmissions}, \quad (11c)$$

$$CO_{norm} = \frac{COEmissions}{MaxCOEmissions}, \quad (11d)$$

Combine Normalised Values

- Cost function, C, is the weighted sum of these normalized factors:

$$C = w_{Fuel} \times Fuel_{norm} + w_{NOx} \times NOx_{norm} + w_{HC} \times HC_{norm} + w_{CO} \times CO_{norm} \quad (12)$$

Adjustments to the weighting in the cost function is needed for UK regulation and public health, which emphasise NOx reduction and fuel economy (18).

UK Weighting Values

Fuel Consumption: $w_{Fuel} = 0.3$

NOx Emissions: $w_{NOx} = 0.4$

HC Emissions: $w_{HC} = 0.2$

CO Emissions: $w_{CO} = 0.1$

Rationale for UK Adjustments

NOx Emissions (0.4): Reducing NOx emissions is a priority because of impact on air quality and public health (18). High levels of NOx contribute to respiratory problems and environmental damage, so NOx emissions have a higher weight of 0.4.

Fuel Consumption (0.3): Fuel costs creates consumer demand for economical vehicles, but it is less important than NOx emissions in terms of health policy. The UK's fuel taxes and energy efficiency goals make fuel economy a substantial factor (19).

HC Emissions (0.2): Hydrocarbon emissions create smog, but they are less prioritized than NOx emissions because of the lower health impact (17). A weight of 0.2 reflects this.

CO Emissions (0.1): Carbon monoxide is controlled in modern engines, and CO has a lower health impact compared to NOx and HC. A weight of 0.1 is sufficient to account for CO without overemphasising it (18).

5.2.2. Calculate and Plot the Cost Function

The Matlab code for the cost Function will be in the appendix.

Plot of each parameter

The average cost function over 1000 iterations is shown in Fig. 9

The normalised values after 1000 iterations are shown in Fig. 10

The matlab code generates hypothetical yet realistic stochastic data, which is then run over 1000 iterations to show which engine speed is the best. The result is usually 2330-2340 RPM.

5.2.3. Design of the Engine Speed Controller

The controller's target speed is 2335 RPM. Implement a PID controller or similar feedback mechanism that adjusts throttle or fuel injection to keep the engine operating at the target speed. If power demand changes, the controller can dynamically adjust, seeking the closest point to the target speed.

5.3. Commercial Aspects

5.3.1. Fuel vs Electricity Cost

Cost section added to the Matlab code. The results are thus:

Cost of electricity for 300 km: £10.40

Cost of fuel for 300 km: £44.30

Cost of electricity per kWh: £0.52

Cost of fuel per kWh: £4.83

It is cheaper to use electricity than fuel. Consider increasing the battery size.

5.3.2. Government Policy

Government policies have influenced the automotive market for EVs, PHEVs, and HEVs. Through financial incentives, such as subsidies, tax credits, and tax exemptions make EVs and PHEVs more affordable, boosting sales. For example, Norway's VAT exemptions have made it a leading EV market.

Governments often have emissions regulations. Strict emissions targets (e.g., EU CO₂ limits, U.S. CAFE standards) push carmakers to make EV and PHEV cars to avoid penalties.

They also offer R&D Funding often. Governments support R&D in battery tech and charging infrastructure, helping lower costs and improve accessibility. These car improvements make people buy EV, PHEV and HEV cars, increasing sales.

6. C3 - Design and Development: Series Hybrid Modelling and Control

6.1. Model Description

The model is shown in Fig. 11.

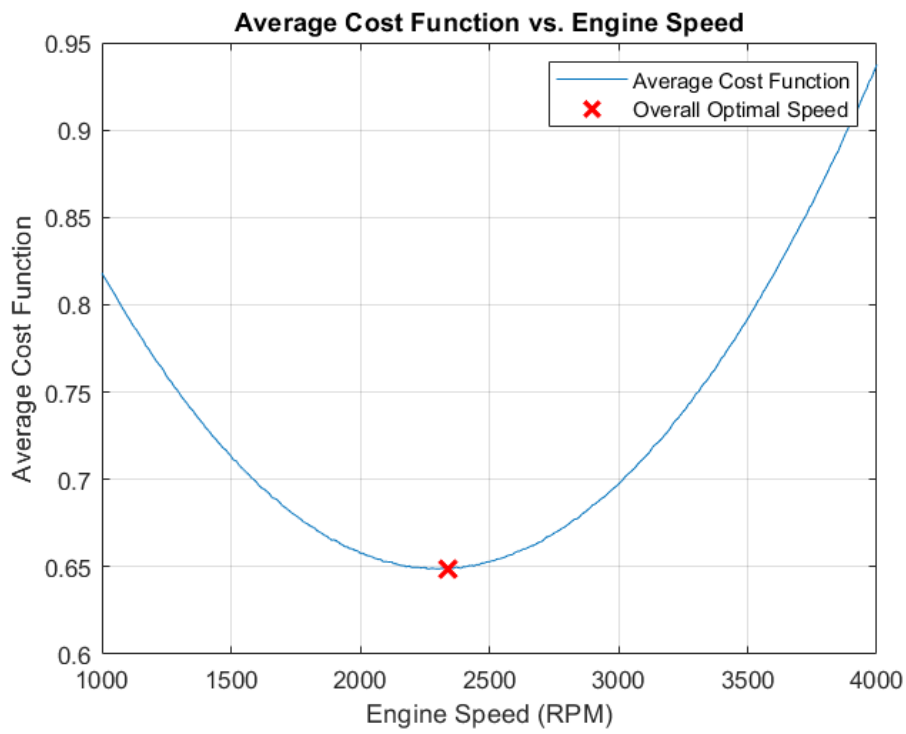


Fig. 9: Average Cost Function vs. Engine Speed(RPM) after 1000 iterations

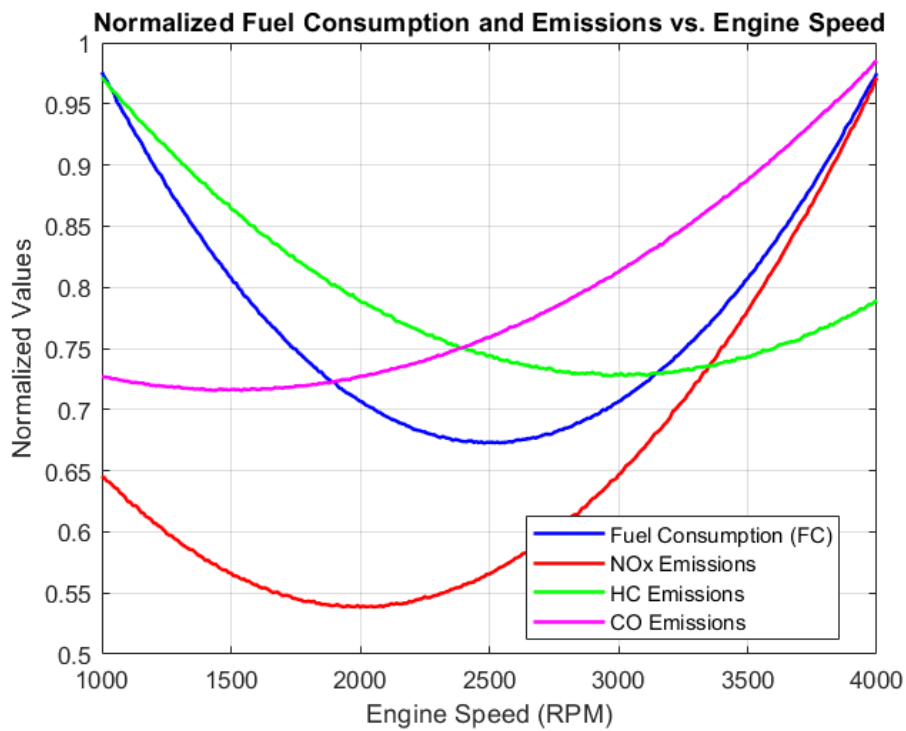


Fig. 10: Normalised values after 1000 iterations

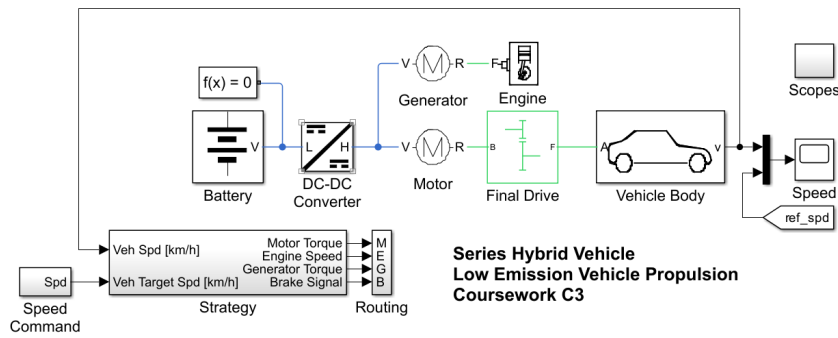


Fig. 11: C3 Simulink Model

The Simulink model simulates a Series Hybrid Electric Vehicle. Key components are a battery, DC-DC converter, electric motor, generator, engine, and final drive system. The model uses a control strategy block to manage motor torque, generator operation, and braking signals based on the difference between the vehicle's target and actual speeds. The battery supplies power to the motor by the DC-DC converter, while the engine-generator setup either powers the motor or recharges the battery. Vehicle dynamics and performance are visualized through a scope block.

This SHEV architecture ensures the engine operates solely as a generator, improving energy efficiency and reducing emissions. Similar designs can be seen in vehicles like the Chevrolet Volt and BMW i3 REx, where the engine acts as a range extender.

6.2. Power of powertrain components

The power profiles of motor power, engine power, generator power, and battery power, alongside vehicle speed, are shown in Fig. 12.

The power profiles show four distinct phases: acceleration, cruising, deceleration, and steady-state.

During acceleration (0-50s), motor power increases to meet torque demands. It stabilizes during cruising (50-200s) to maintain constant speed. In deceleration (200-250s), motor power becomes negative, indicating regenerative braking. In steady-state operation (250-400s), motor power drops to zero, as less effort is needed for lower speed.

Engine and generator power remain nearly constant during cruising and steady-speed phases, reflecting optimal efficiency. The engine is inactive during acceleration and deceleration, reducing emissions and fuel consumption, while the generator converts engine power into electricity.

Battery power fluctuates between supplying power and being recharged. During acceleration, the battery provides power to the motor. During cruising, the battery is recharged by the generator. During deceleration, the battery power sharply spikes negative, showing energy recovery via regenerative braking.

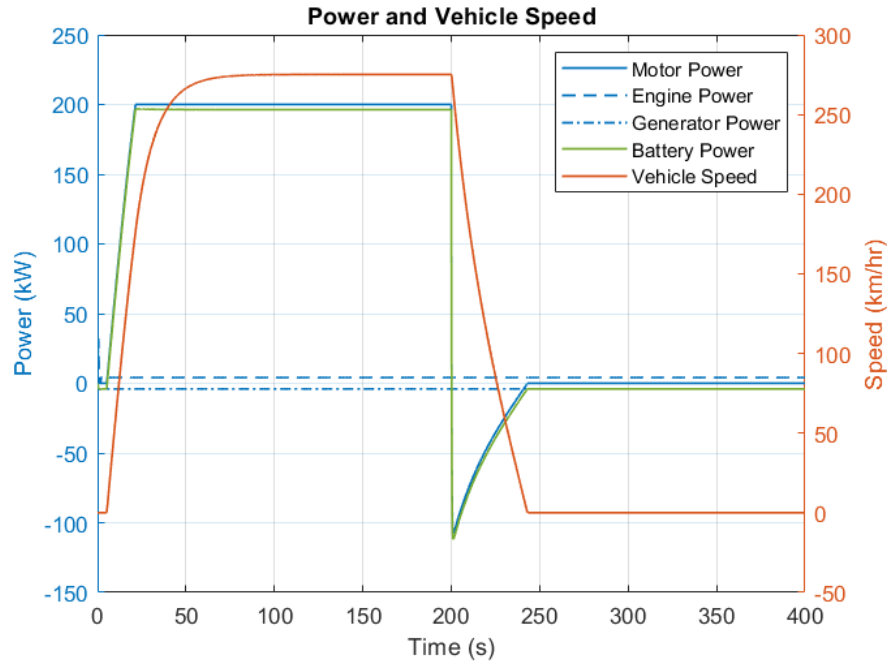


Fig. 12: Power of powertrain components of example vehicle

The motor ensures smooth transitions between these energy phases.

6.3. Electrical Losses

The electrical losses in the specified vehicle are shown in Fig. 13.

Motor losses are visible throughout the vehicle's operation, especially during acceleration (0–50 seconds) and cruising (50–200 seconds). These losses come from electrical resistance, hysteresis, and eddy current losses in the motor's magnetic core. During acceleration, the high current demanded creates higher losses.

Generator losses include resistive losses in the windings, frictional losses in mechanical components, and magnetic losses like hysteresis and eddy currents. The graph shows generator losses becoming significant during the cruising phase (50–200 seconds) and steady-speed operation (250–400 seconds).

Battery losses are most prominent during acceleration and deceleration phases. During acceleration (0–50 seconds), losses occur due to internal resistance as the battery supplies high current to the motor. During deceleration (200–250 seconds), battery losses from charging inefficiencies as the battery stores energy recovered from regenerative braking. Chemical reactions within the battery contribute to heat generation, further increasing losses.

As can be seen in Fig. 14, when increased to 400V the battery losses become much smaller because of

$i^2 \times R$, but all the other losses remain identical. This makes sense because the only thing changing is the battery.

6.4. Torque Data in Final Drive

In Fig. 15, Final Drive/tB (blue line) represents the input torque. Final Drive/tF (red line) represents the output torque.

Equation 13 gets gear ratio from ratios of torque.

$$\text{Gear Ratio} = \frac{\text{Input Torque (to the final drive)}}{\text{Output Torque (from the final drive)}} \quad (13)$$

From the figure, values of tB is $\tilde{4}50$ Nm between 200–240s, and tF is 150 in the same time frame, which gives a value of $\tilde{3}$ for the gear ratio. If checked the simulink model also says the ratio is three so that makes sense.

6.5. Gear Ratio Optimisation

Gear ratio optimisation requires a cost function. To save time, this report has devised a matlab script that will be in the appendix to deal with this. In order to do this the gear ratio had to be deleted from the model workspace and initialised in the base workspace by the code script. It provides Fig. 16.

This shows us that 4 is the best gear ratio.

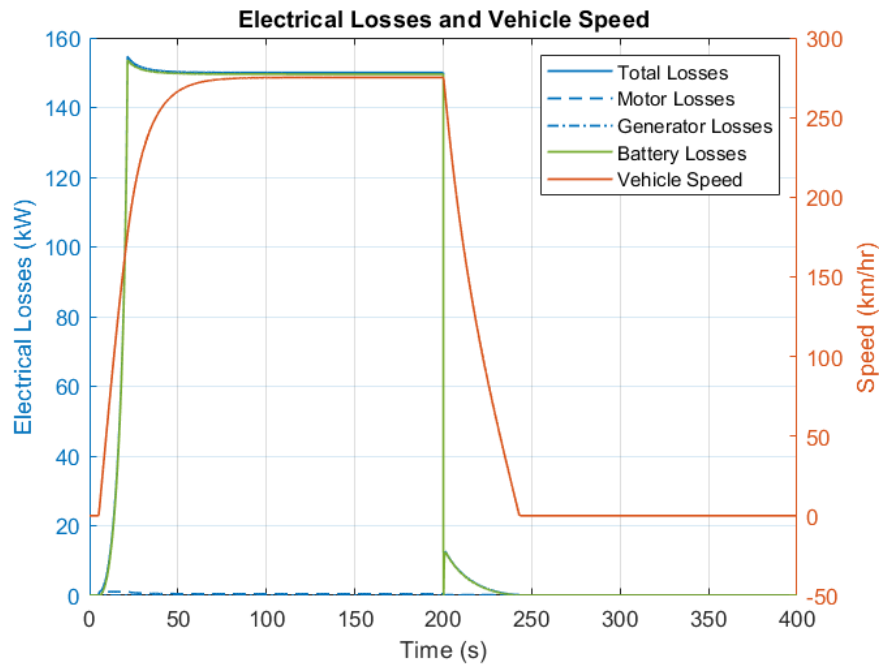


Fig. 13: Electrical losses of specified vehicle

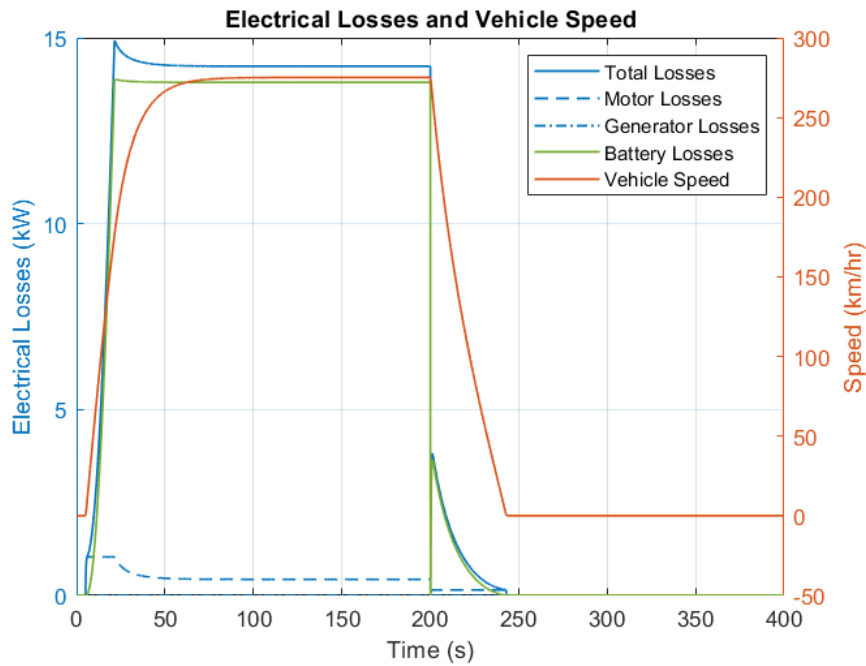


Fig. 14: Electrical losses of specified vehicle with a 400V battery

6.6. Control Strategy for FTP cycle

By varying the RPM the fuel consumption was lowest at 2500 RPM. By varying the torque the best efficiency that could be got was at 70 Nm.

6.7. SoC Management Control System

When developing a control strategy to vary the engine speed and generator torque demand dynamically to manage the battery state of charge so that the state of charge at the end of the FTP is the

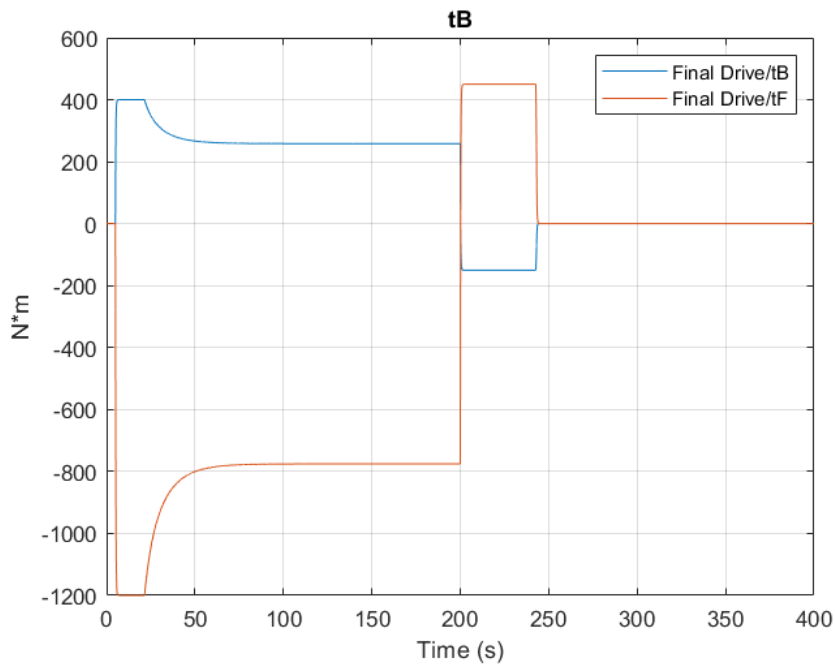


Fig. 15: Torque Data in Final Drive

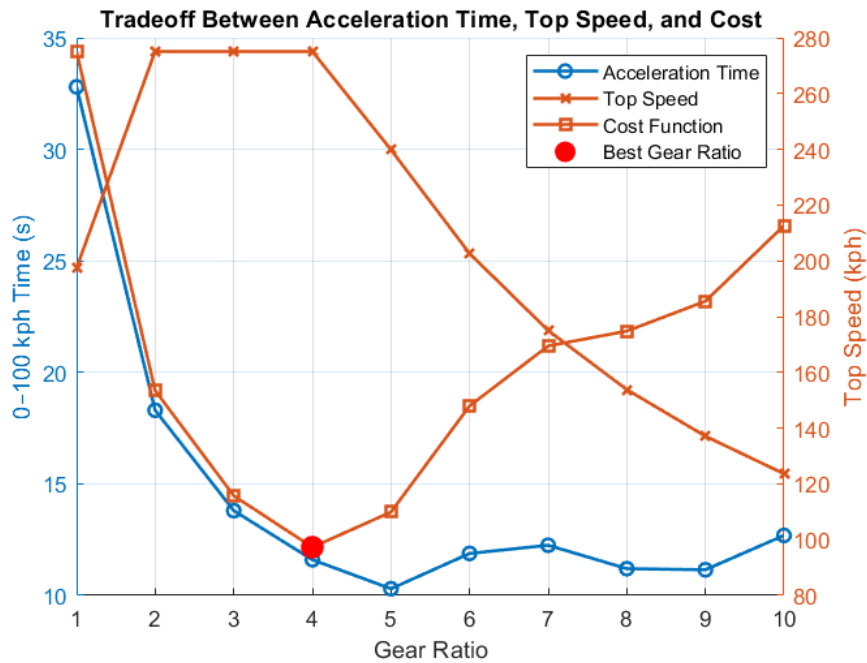


Fig. 16: Top speed and acceleration time against gear ratio with cost function and best gear ratio

same as at the start, the obvious answer would be to completely disconnect battery, and that would ensure that the state of charge would not change. However, it is probably best to come up with an actual control strategy that is a bit more clever.

As shown in Fig. 17 of the entire system, the battery state of charge is taken directly from the battery out of the calculations section.

This is then put into the SOC controller, inside the strategy block as shown in Fig. 18. Also put

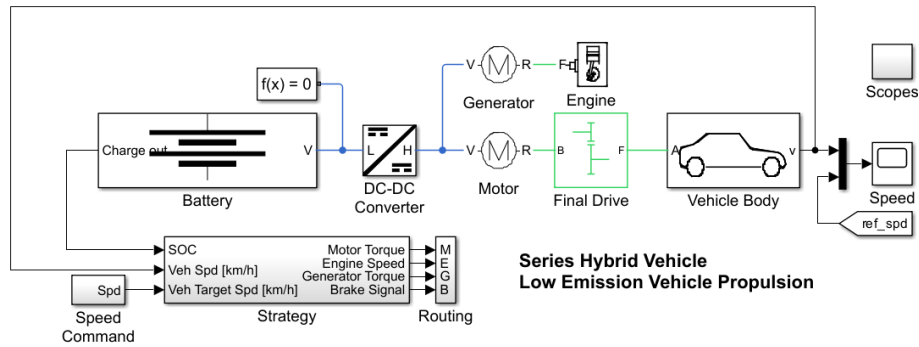


Fig. 17: Entire simulink system with state of charge taken from the battery

into the SOC controller is the target state of charge, which is the original state of charge. After looking at scopes this is 19. Also shown in this figure is where the signal goes after the SOC controller.

In Fig. 19 is the inside of the SOC controller. It brings in the SOC and Target SOC, subtracts and plugs them into a discrete PI controller. It goes to the generator torque controller, and also through a saturation block before reaching engine speed. This saturation controller limits the speed to below 7000 RPM (maximum engine speed) but above 500 RPM (stalling speed).

7. C4: Reflective Report

7.1. Interesting Discoveries

The most interesting discovery was understanding the complexity of hybrid vehicle powertrain systems, especially how each component (motor, generator, battery) must be tuned to optimise efficiency. I also learned about the real-world challenges of energy recovery and fuel consumption in vehicles like the Chevrolet Volt..

7.2. Challenging Moments

The most challenging aspect was optimising the control strategy, particularly balancing the battery state of charge whilst minimising fuel consumption. Integrating the subsystems and making sure they worked efficiently under all conditions required extensive testing and problem-solving.

7.3. Powerful Learning Moments

The most powerful learning moment occurred when I realised how small changes in gear ratio or torque could have large impacts on system performance. The iterative testing process helped refine the model.

7.4. Final Best Solution

I knew I had found the best solution when the powertrain's performance was consistent across all operating phases, with energy efficiency and fuel consumption aligned with the project's goals. This was confirmed by stable system operation and minimal losses.

7.5. Real-World Relevance

This project is highly relevant to real-world hybrid vehicle development, where managing fuel efficiency and reducing emissions is essential. It mirrored challenges faced in vehicles like the BMW i3, providing practical insights into sustainable transportation.

7.6. Strengths and Areas for Improvement

My strength lies in problem-solving, but simulink block modeling is an area I could improve. It took me a long time when writing the gear ratio script to realise i was just updating the variable 'GearRatios' in the base workspace and not the model workspace. I had to delete it to make it work.

7.7. Personal Improvement Focus

I aim to improve my simulink block modelling, especially variables and fully utilising the simulink model workspace, to enhance my efficiency in future projects.

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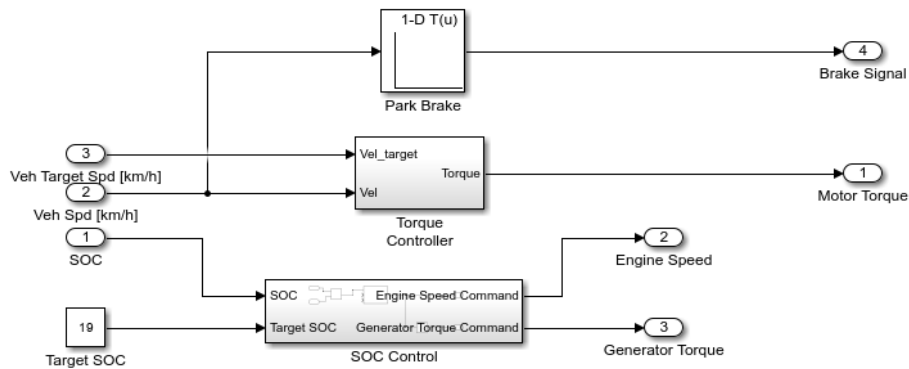


Fig. 18: Simulink strategy subsystem

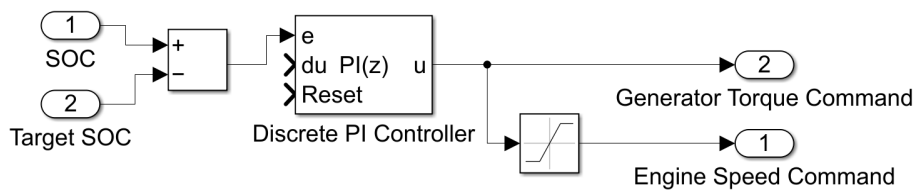


Fig. 19: Simulink SOC subsystem

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transport-a-better-greener-britain.pdf

8. Appendix

o

.

```
close all;
clear all;
clc;
```

Initial Section

```
% Load drive cycle data
WLTC(:,1) = xlsread('WLTP-DHC-12-07e.xls','WLTC_class_3','C8:C1808'); % Time
[s]
WLTC(:,2) = xlsread('WLTP-DHC-12-07e.xls','WLTC_class_3','E8:E1808'); %
Speed [kph]

% Vehicle and environmental parameters
m_vehicle = 900; % Vehicle mass [kg]
CdA = 0.3; % Drag coefficient
z_RR = 0.15/9.81; % Rolling resistance coefficient
g = 9.81; % Gravity [m/s^2]
constant_RR = 40; % Rolling resistance offset [N]

% Define efficiencies
eff_generator_motor = 0.79; % Generator to motor net efficiency
eff_battery_motor = 0.91; % Battery to motor net efficiency
eff_grid_battery = 0.91; % Grid to battery net efficiency
eff_gear = 0.95; % Gear efficiency

% Calculate average speed
v_av = sum(WLTC(:,2)) / WLTC(end,1); % Average speed [kph]

% Convert speed and calculate acceleration
t_WLTC = WLTC(:,1); % Time [s]
v_WLTC = WLTC(:,2) / 3.6; % Speed [m/s]
a_WLTC = [diff(v_WLTC); 0]; % Acceleration [m/s^2]
a_WLTC = max(a_WLTC, 0); % Only positive acceleration

% Forces and power calculations
rho_amb = 1.225; % Air density [kg/m^3]
F_drag = 0.5 * CdA * rho_amb * v_WLTC.^2; % Drag force [N]
F_acceleration = m_vehicle * a_WLTC; % Acceleration force [N]
F_rolling = constant_RR; % Rolling resistance force [N]

% Total force on vehicle and power requirements at the wheels
F_vehicle = F_acceleration + F_drag + F_rolling;
power_wheel = F_vehicle .* v_WLTC / 1000; % Power at wheels [kW]

% Adjust power delivered by the battery (battery-driven power)
power_battery = power_wheel / (eff_battery_motor * eff_gear); % Power from
battery [kW]

% For engine-driven calculations, account for generator-to-motor and gear
efficiency
power_engine_to_wheels = power_wheel / (eff_generator_motor * eff_gear); %
Engine power to wheels [kW]
```

```

% Cumulative energy for battery usage
energy_battery = cumsum(power_battery) / 1000; % Energy from battery [MJ]

% Cumulative energy for engine use
energy_engine = cumsum(power_engine_to_wheels) / 1000; % Energy from engine
[MJ]

% Plot speed over time
figure(1)
plot(t_WLTC, WLTC(:,2))
title('WLTC Drive Cycle: Speed over Time')
ylabel('Speed [kph]')
xlabel('Time [s]')

% Plot acceleration over time
figure(2)
plot(t_WLTC, a_WLTC)
title('Vehicle Acceleration over Time')
ylabel('Acceleration [m/s^2]')
xlabel('Time [s]')

% Plot forces over time
figure(3)
hold on
plot(t_WLTC, F_acceleration, 'b', 'DisplayName', 'Acceleration Force')
plot(t_WLTC, F_drag, 'r', 'DisplayName', 'Drag Force')
plot(t_WLTC, F_rolling * ones(size(t_WLTC)), 'g', 'DisplayName', 'Rolling
Resistance')
hold off
title('Forces Acting on Vehicle over Time')
ylabel('Force [N]')
xlabel('Time [s]')
legend

% Plot power and cumulative energy
figure(4)
hold on
plot(t_WLTC, power_battery, 'DisplayName', 'Battery Power [kW]')
plot(t_WLTC, energy_battery, 'DisplayName', 'Battery Energy [MJ]')
plot(t_WLTC, power_engine_to_wheels, 'DisplayName', 'Engine Power [kW]')
plot(t_WLTC, energy_engine, 'DisplayName', 'Engine Energy [MJ]')
hold off
title('Power and Energy Consumption over Time')
ylabel('Power [kW] / Energy [MJ]')
xlabel('Time [s]')
legend

% Calculate average energy consumption per km
total_distance = max(cumsum(v_WLTC)) / 1000; % Total distance [km]
avg_energy_per_km = (energy_battery(end) * 1000) / total_distance; % [Wh/km]

% Define battery capacity and calculate EV range
battery_capacity_kWh = 20; % Battery capacity [kWh]

```

```

battery_capacity_Wh = battery_capacity_kWh * 1000; % Battery capacity [Wh]
ev_range_km = battery_capacity_Wh / avg_energy_per_km; % EV range [km]

% Define total required range and engine range
required_range_km = 300; % Required range [km]
engine_range_km = required_range_km - ev_range_km; % Range provided by the
engine [km]

% Fuel consumption calculations
BSFC = 220; % Brake-Specific Fuel Consumption [g/kWh]
engine_energy_needed_kWh = (avg_energy_per_km * engine_range_km) / (1000 *
eff_generator_motor * eff_gear);
fuel_needed_grams = engine_energy_needed_kWh * BSFC; % Fuel needed [g]
fuel_needed_liters = fuel_needed_grams / 750; % Assuming 750 g/L fuel density

% Display results
fprintf('Average energy consumption: %.2f Wh/km\n', avg_energy_per_km);
fprintf('EV range (battery only): %.2f km\n', ev_range_km);
fprintf('Engine range needed: %.2f km\n', engine_range_km);
fprintf('Fuel required for 300 km: %.2f liters\n', fuel_needed_liters);

% Additional bar charts with different colors
figure(5)

% Range distribution bar chart
subplot(2,1,1)
bar([ev_range_km, engine_range_km, required_range_km], 'FaceColor', 'flat')
colormap(jet(3)) % Use different colors
set(gca, 'XTickLabel', {'EV Range', 'Engine Range', 'Total Required Range'})
ylabel('Range [km]')
title('Range Distribution')
colororder({'#0072BD', '#D95319', '#EDB120'}) % Set custom colors for each bar

% Energy requirements bar chart
subplot(2,1,2)
bar([battery_capacity_kWh, engine_energy_needed_kWh], 'FaceColor', 'flat')
colormap(jet(2)) % Use different colors
set(gca, 'XTickLabel', {'Battery Energy', 'Engine Energy Needed'})
ylabel('Energy [kWh]')
title('Energy Requirements')
colororder({'#4DBEEE', '#A2142F'}) % Set custom colors for each bar

```

Hydrogen Section

```

% Hydrogen fuel cell calculations
fuel_cell_efficiency = 0.60; % 60% efficiency for fuel cell
hydrogen_energy_density_MJ_per_L = 5.6; % Energy density of hydrogen at 70
MPa [MJ/L]

% Total energy needed from hydrogen
total_energy_needed_hydrogen_Wh = engine_energy_needed_kWh /
fuel_cell_efficiency; % Energy from hydrogen [Wh]

```

```

% Calculate hydrogen mass required
hydrogen_volume_needed_liters = total_energy_needed_hydrogen_Wh /
hydrogen_energy_density_MJ_per_L; % Mass of hydrogen [kg]

% Display result
fprintf('Hydrogen fuel cell tank volume needed: %.2f liters\n',
hydrogen_volume_needed_liters);

```

Cost Section

Given Prices

```

electricity_price = 0.52; % £/kWh
fuel_price = 1.48; % £/L
BSFC = 230; % g/kWh (updated BSFC value)

engine_energy_needed_kWh = (avg_energy_per_km * engine_range_km) / (1000 *
eff_generator_motor * eff_gear);
fuel_needed_grams = engine_energy_needed_kWh * BSFC; % Fuel needed [g]
fuel_needed_liters = fuel_needed_grams / 750; % Assuming 750 g/L fuel density

electricity_cost = battery_capacity_kWh * electricity_price; % Cost of
electricity in £
fuel_cost = fuel_needed_liters * fuel_price; % Cost of fuel in £
electricity_cost_kwh = 0.52;
fuel_cost_kwh = 1.48*750/BSFC;

fprintf('Cost of electricity for 300 km: £%.2f\n', electricity_cost);
fprintf('Cost of fuel for 300 km: £%.2f\n', fuel_cost);
fprintf('Cost of electricity per kWh: £%.2f\n', electricity_cost_kwh);
fprintf('Cost of fuel per kWh: £%.2f\n', fuel_cost_kwh);

% Decision on tank/battery sizing to reduce costs
if electricity_cost_kwh < fuel_cost_kwh
    disp('It is cheaper to use electricity than fuel. Consider increasing
the battery size.');
```

```

elseif fuel_cost_kwh < electricity_cost_kwh
    disp('It is cheaper to use fuel than electricity. Consider increasing
the fuel tank size.');
```

```

else
    disp('Electricity and fuel costs are equal. Either option is viable.');
```

```

end

```

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```

clc
clear
close all

% Define the range of gear ratios to test
GearRatios = linspace(1, 10, 10); % Gear ratio values from 1 to 10
AccelerationTimes = zeros(size(GearRatios)); % Preallocate array for
acceleration times
TopSpeeds = zeros(size(GearRatios)); % Preallocate array for top speeds
Costs = zeros(size(GearRatios)); % Preallocate array for costs

% Define weights for the cost function
w_accel = 0.6; % Weight for acceleration time (0-100 kph)
w_speed = 0.4; % Weight for top speed

% Loop through each gear ratio
for i = 1:length(GearRatios)
    % Update GearRatio in the base workspace
    GearRatio = GearRatios(i); % Current gear ratio
    assignin('base', 'GearRatio', GearRatio); % Update the base workspace
    variable
    disp(['Testing Gear Ratio: ', num2str(GearRatio)]); % Debugging: Check
    applied gear ratio

    % Run the simulation
    sim('SeriesHybridTransmission'); % Simulate the model

    % Extract velocity data from the simulation logs
    vms =
    simlog_SeriesHybridTransmission.Vehicle_Body.Vehicle_Body.V.series.values; %
    Velocity in m/s
    time =
    simlog_SeriesHybridTransmission.Vehicle_Body.Vehicle_Body.V.series.time; %
    Time in seconds
    v = vms * 3.6; % Convert velocity from m/s to km/h (1 m/s = 3.6 km/h)

    % Calculate top speed
    topSpeed = max(v); % Maximum velocity in km/h
    TopSpeeds(i) = topSpeed;

    % Calculate 0-100 kph acceleration time
    target_speed = 100; % Target speed in km/h
    idx = find(v >= target_speed, 1); % Find the first index where velocity
    reaches or exceeds 100 km/h
    if ~isempty(idx)
        accelTime = time(idx); % Time at which 100 km/h is reached
    else
        accelTime = NaN; % If target speed is not reached
    end
    AccelerationTimes(i) = accelTime;

    % Compute the cost function

```

```

    if ~isnan(accelTime)
        % Normalize parameters (min-max normalization)
        normAccel = (accelTime - min(AccelerationTimes)) /
(max(AccelerationTimes) - min(AccelerationTimes) + eps);
        normSpeed = (topSpeed - min(TopSpeeds)) / (max(TopSpeeds) -
min(TopSpeeds) + eps);
        Costs(i) = w_accel * normAccel + w_speed * (1 - normSpeed); %
Minimize cost
    else
        Costs(i) = Inf; % Penalize configurations that cannot reach 100 kph
    end
end

% Find the best gear ratio (minimum cost)
[~, bestIndex] = min(Costs);
bestGearRatio = GearRatios(bestIndex);
disp(['Best Gear Ratio: ', num2str(bestGearRatio)]);

% Plot the tradeoff between acceleration time, top speed, and cost function
figure;
hold on;
yyaxis left; % Plot acceleration time on the left y-axis
plot(GearRatios, AccelerationTimes, '-o', 'LineWidth', 1.5, 'DisplayName',
'Acceleration Time');
ylabel('0-100 kph Time (s)');
yyaxis right; % Plot top speed on the right y-axis
plot(GearRatios, TopSpeeds, '-x', 'LineWidth', 1.5, 'DisplayName', 'Top
Speed');
ylabel('Top Speed (kph)');

% Overlay the cost function on the same graph (normalized for visual clarity)
normalizedCosts = Costs / max(Costs); % Normalize cost to match the scale
plot(GearRatios, normalizedCosts * max(TopSpeeds), '-s', 'LineWidth', 1.5,
...
'DisplayName', 'Cost Function', 'Color', [0.85, 0.33, 0.1]);

% Highlight the best gear ratio
plot(bestGearRatio, normalizedCosts(bestIndex) * max(TopSpeeds), 'ro', ...
'MarkerSize', 10, 'MarkerFaceColor', 'r', 'DisplayName', 'Best Gear
Ratio');

% Add labels and legend
xlabel('Gear Ratio');
title('Tradeoff Between Acceleration Time, Top Speed, and Cost');
legend show;
grid on;
hold off;

% Display results in the console
disp('Gear Ratio Analysis:');
disp(table(GearRatios', AccelerationTimes', TopSpeeds', Costs', ...
'VariableNames', {'GearRatio', 'AccelerationTime', 'TopSpeed', 'Cost'}));

```

