What's the most efficient way to drive a car?

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Abstract

Eco-driving is a simple and effective way to improve fuel efficiency and reduce emissions. In this project, a computational model was developed to investigate what are the optimal driving strategies for a 2017 Ford Fiesta with an internal combustion engine across different road profiles, including flat, uphill ,downhill and mixed terrains. The model combined vehicle dynamics,gear shifting, engine performance data, along with optimisation techniques to find throttle profiles that minimise fuel usage while meeting a time constraint. The results showed that using a pulse and glide approach reduces energy consumption by up to 38.72% compared to constant throttle input driving. The energy savings found heavily depended on the road gradient with the greatest reductions in energy consumption found when the vehicle is travelling downhill. The project shows that adapting one's driving style to the terrain can achieve significant fuel savings.

Contents

1 Introduction

The question of how to drive a car efficiently has never been more relevant with high fuel prices and increasing CO_2 emissions. The transportation sector is a major contributor to anthropogenic greenhouse gases, accounting for 28% of greenhouse gas emissions, 80% of which comes from road transport [1]. While this sector is slowly decarbonising through the transition to hybrid electric vehicles (HEVs) and electric vehicles (EVs), individuals driving style can have significant impact on overall energy consumption. Efficient driving, often called eco-driving, represents a driving technique that aims to reduce fuel consumption and environmental impact.

Eco-driving represents a combination of many different techniques to improve vehicle efficiency such as smooth braking and acceleration, anticipating traffic flow and signals, maintaining a steady speed below or at the speed limit plus minimising the use of non-essential features such as air conditioning and heated seats. Some advocates of eco-driving also state that keeping the car in good condition with regular automobile maintenance, for example making sure the tyres are kept at the manufacturer's optimum pressure and the changing of air filters, leads to improved fuel efficiency. This report focuses solely on driving behaviour. An additional benefit of eco-driving is improved safety, with fewer accidents and fatalities. Studies have shown that employing an eco-driving technique can lead to a 4-25% energy saving[2][3]. One particularly effective eco-driving technique discussed in current literature is the "Pulse and Glide" (PnG) which is a driving strategy that works by alternating between acceleration and deceleration. Instead of maintaining a steady speed, the PnG strategy accelerates (pulse) up to a high velocity and then coasts (glide) to a low velocity. In [4], researchers found that the PnG strategy achieves a fuel saving of 15% to 35% from 22mph to 67mph in simulation. Later on in [5], it was found that the PnG method had a 7-8% fuel saving at 50km/h.

While substantial work has been done on eco-driving strategies, current research often uses controlled or limited driving conditions, focusing on flat or uniform terrains. The objective of this report is to extend our current understanding by developing a computational model to identify the optimal driving strategies for vehicles powered by internal combustion engines which focuses on identifying the optimal throttle profile across a wide range of road profiles. To ensure comprehensive applicability, the model considers multiple road profiles, from a simple flat terrain to a more complex terrain with varying gradients. This approach aims to provide actionable recommendations to improve overall fuel economy, reduce emissions, and enhance the understanding of driving behaviours for real world applications.

The remainder of this report is structured as follows: Section 2 will discuss the computational modelling methodology and the assumptions used; Section 3 presents the results of the simulation: Section 4 discusses these results; and finally Section 5 summarizes key findings and recommends best driving practices as well as further research.

2 Description of how the project was conducted

In this chapter, the models used in this study are presented. The chapter is divided into the vehicle dynamics model, the gear shifting model, the engine mapping, the internal optimiser and the external optimiser.

A 2017 Ford fiesta 3dr with a 1.1-litre Ti-VCT (70 PS) manual engine was chosen as the reference vehicle for this study. The reason for this choice was that it represents a common road vehicle and that it has readily available information for parameters such as mass, drag coefficient, frontal area and engine power.

Building on this, the basic methodology involves simulating a journey where the car travels a fixed distance while being required to achieve a specified average speed. During each simulation, the car is allowed to shift gears and vary the throttle input to minimise energy consumption. Additionally, the road profiles are adjusted across runs to incorporate different inclines as seen in Figure 1. This approach allows the study to evaluate how changing road conditions and driving strategies impact overall efficiency.

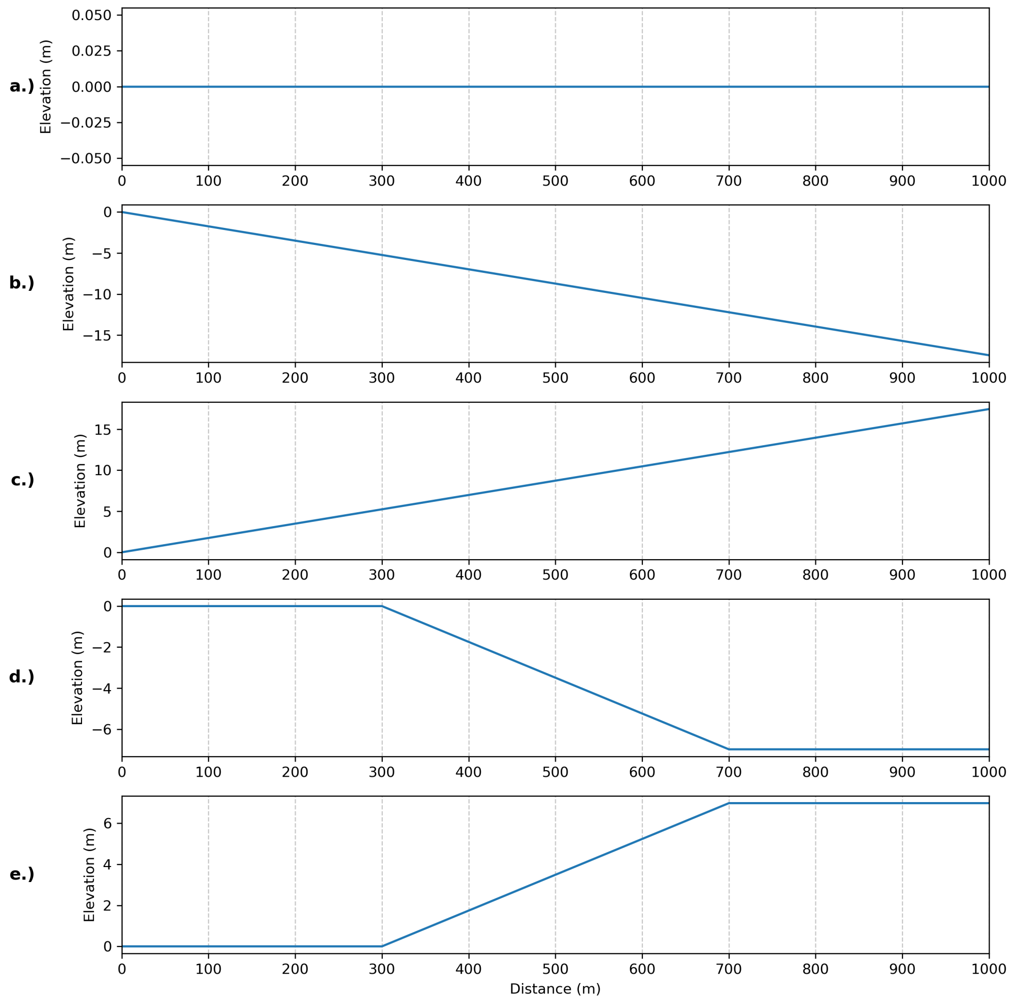

Figure 1: Simple and varied road elevation profiles used in the simulation: a.) flat road, b.) constant downhill slope of 1°, c.) constant uphill slope of 1°, d.) flat section followed by a 1° downhill slope and then flat again, e.) flat section followed by a 1° uphill slope and then flat again.

To carry out the simulations, two optimisers are used. A throttle profile describes how the throttle input (and therefore power) varies across different segments of the journey. The aim is to find the optimal throttle profile that delivers enough power in each segment to achieve the required average speed while using the least amount of energy overall. The internal optimiser works by scaling a given throttle profile to meet the speed requirement, while the external optimiser adjusts the shape of the throttle profile itself to minimise total energy consumption.

2.1 Gear shifting

The gear shifting model has been developed so that it upshifts at a fixed RPM—3000 RPM in the case shown in Figure 2. As the road speed increases, the vehicle remains in a given gear until the shift RPM is reached, at which point it shifts to the next gear. This process repeats as the vehicle accelerates. In Figure 2, the vehicle follows the first gear curve up to 3000 RPM before shifting to second gear. This pattern continues through the subsequent gears until the highest gear is reached, at which point no further upshifts are possible. The vehicle then continues to accelerate along the fifth gear curve until it reaches the maximum RPM.

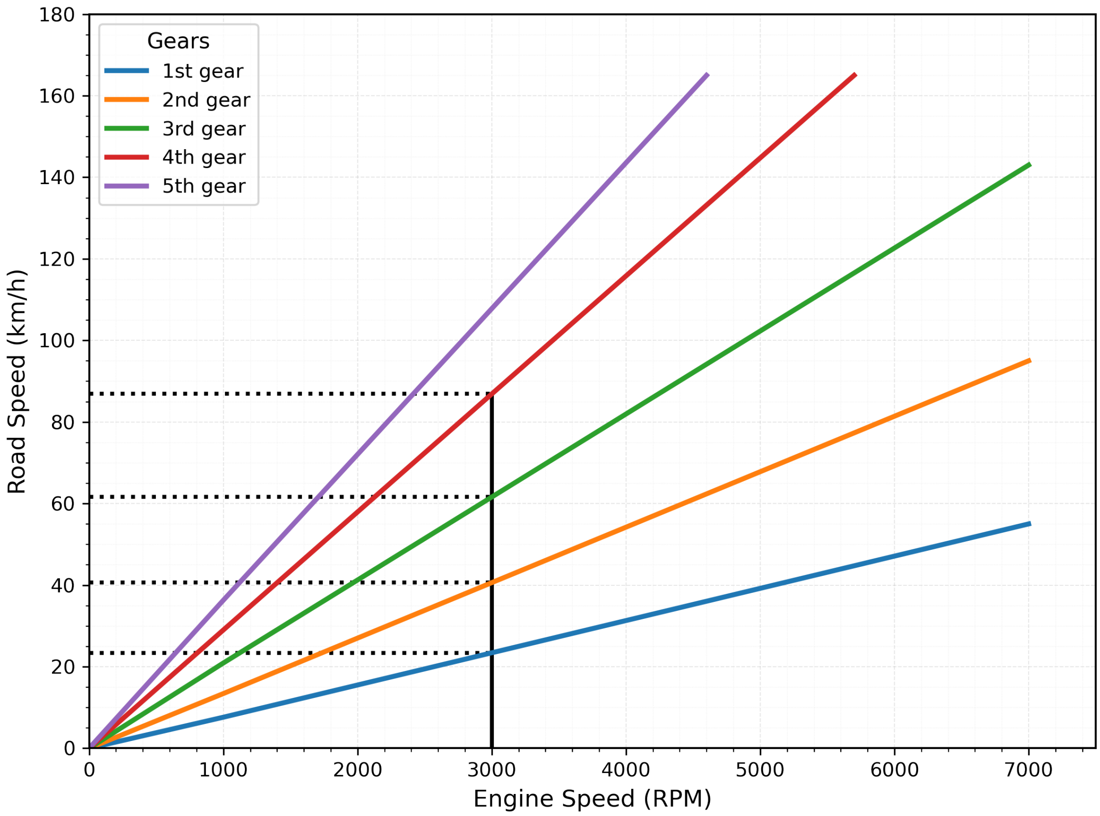

Figure 2: Relationship between engine speed (RPM) and road speed for each gear. Figure adapted from [6].

2.2 Engine mapping

Engine mapping is the process of characterising how an engine delivers torque or power based on engine speed (rpm) and throttle position(load). This data is organised into a two-dimensional map to allow the engines performance to be controlled under varying conditions. To do this in the real world engine control units (ECUs) use this map to find the optimal fuel and ignition settings for any combination of RPM and throttle input,ensuring both performance and safety while driving.

In this project, the engine map has been simplified by modelling the power vs rpm curve. This omits the load axis, however a throttle profile is incorporated separately in the model to determine how much of the available power at a given RPM is used. The effective engine power is then given by:

$$P_{true} = P_{available} \times \text{throttle position} \tag{2.1}$$

Here, the *throttle position* is a dimensionless control input ranging from 0 to 1, where 0 represents no power demand (foot off the pedal) and 1 represents full power demand (pedal fully pressed). To better represent real engine behaviour,the power curve from [7] has been adapted to have a minimum power level at low RPMs. This simulates engine idling, where the engine must produce some power to keep itself running. Figure 3 shows the resultant curve, which is based on test data but modified to account for idle behaviour.

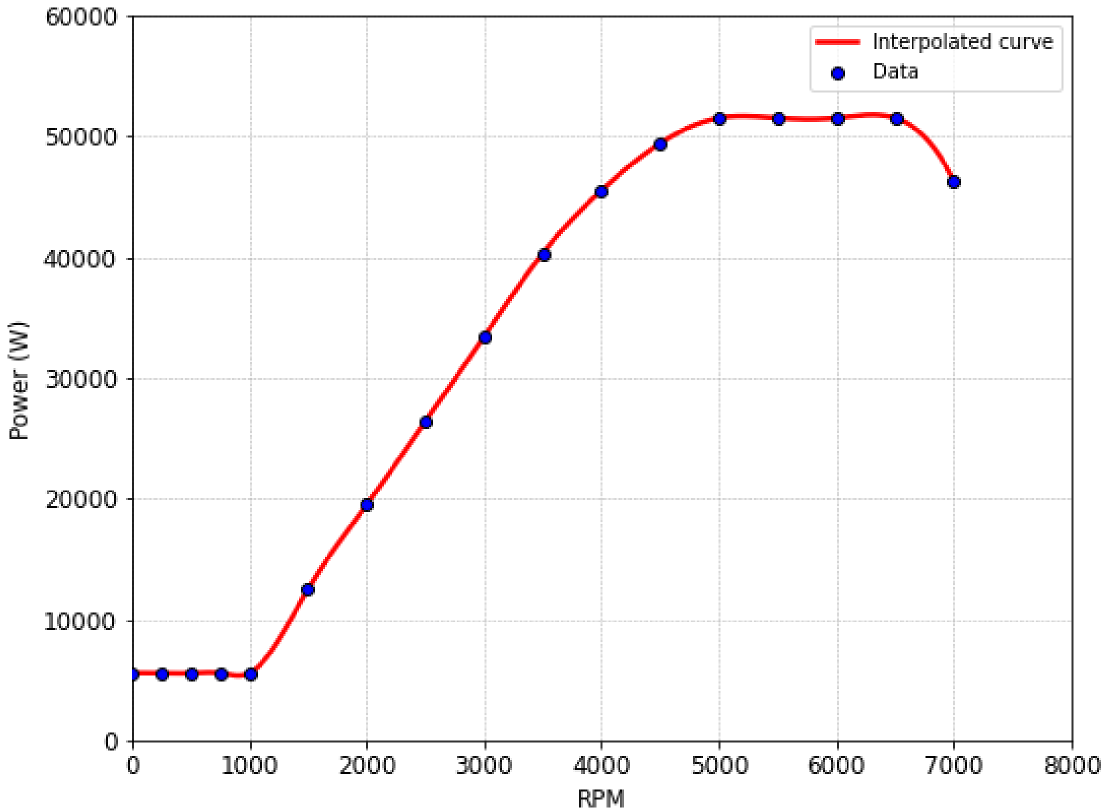

Figure 3: Power versus RPM curve for the Ford Fiesta 1.1 Ti-VCT engine. Figure adapted from [7].

2.3 Vehicle dynamics

2.3.1 Overview

We model the motion of the vehicle as a point mass travelling up an incline of angle θ. The aim of this is to calculate the acceleration and position over time. This is done by summing all forces along the slope direction and using Newton's second law of motion. Two key assumptions have been made:

1. The vehicle is treated as a point mass m.
2. P_{true} is taken to be the net power at the wheel.

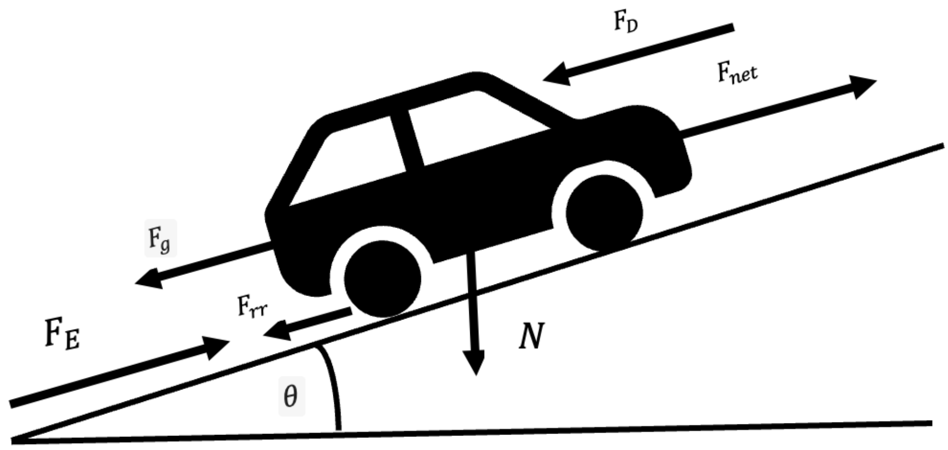

Figure 4: Diagram illustrating the forces acting on a vehicle travelling up an incline.

2.3.2 Forces

There are a number of different forces that act on the car during motion.The effective engine force F_E is calculated from the actual engine power output P_{true} and the velocity v of the vehicle, using the following expression:

$$F_E = \frac{P_{true}}{v} \tag{2.2}$$

The aerodynamic drag force F_D, which opposes the motion of the vehicle, is dependent on the air density ρ, vehicle velocity, drag coefficient C_D, and frontal area A:

$$F_D = \frac{1}{2}\rho v^2 C_D A \tag{2.3}$$

The normal force acts perpendicular to the road surface and depends on the vehicle's mass, gravitational acceleration, and the slope angle of the road. Here, N is the normal force, m is the vehicle mass, g is the acceleration due to gravity, and θ is the slope angle of the road:

$$N = mg\cos(\theta) \tag{2.4}$$

Rolling resistance opposes the vehicle's motion due to friction between the tyres and the road surface. It is proportional to the normal force, where F_{rr} is the rolling resistance force and C_{rr} is the rolling resistance coefficient:

$$F_{rr} = C_{rr}N \tag{2.5}$$

The gravitational component along the slope contributes a force parallel to the inclined road surface, affecting the vehicle's motion depending on whether the slope is uphill or downhill. Here, F_g is the gravitational force component acting along the slope:

$$F_g = mg\sin(\theta) \tag{2.6}$$

A summary of all parameters used in the model can be found in table 1.

2.3.3 Net force and equations of motion

Summing all the forces acting on the vehicle gives the net force, F_{net}. This includes the effective engine force F_E, gravitational force along the slope F_g, aerodynamic drag F_D, and rolling resistance F_{rr}:

$$F_{net} = F_E - F_g - F_D - F_{rr} \tag{2.7}$$

At low velocities, rolling resistance F_{rr} is set to zero, as minimal or no power at the start would otherwise cause the vehicle to roll backwards.

Using Newton's second law, the acceleration a of the vehicle can be calculated from the net force and the vehicle mass:

$$a = \frac{F_{net}}{m} \tag{2.8}$$

Acceleration is then used to update the velocity of the vehicle at each time step. Here, v_t is the current velocity, and $v_{t+\Delta t}$ is the velocity at the next time step, with Δt being the time interval:

$$v_{t+\Delta t} = v_t + a\Delta t \tag{2.9}$$

Finally, velocity is used to update the vehicle's position along the road. Here, d_t is the current position, and $d_{t+\Delta t}$ is the position at the next time step:

$$d_{t+\Delta t} = d_t + v\Delta t \tag{2.10}$$

2.4 Internal optimiser

In order to make sure that the car goes from A to B in a reasonable time a target velocity, v_{target}, is introduced

$$v_{target} = \frac{d_f}{t_c} \tag{2.11}$$

where d_f is the required distance and t_c is the time constraint. At the end of each simulated run (for a given throttle profile $u(x)$)we compute an average velocity $\bar{v}$

$$\bar{v} = \frac{d_f}{T} = \bar{v}(\alpha) \tag{2.12}$$

where T is the time that vehicle travels d_f for a given throttle profile $u(x)$.The optimiser then minimises $f(\alpha)$ where

$$f(\alpha) = |\bar{v} - v_{target}| \tag{2.13}$$

if $\bar{v} \neq v_{target}$ we scale the throttle profile by a scaling factor α.

$$u_{scaled}(x) = \alpha u(x) \tag{2.14}$$

Symbol	Description	Value	units
m	Vehicle mass	1630	kg
g	Acceleration due to gravity	9.81	m/s^2
θ	Road incline angle	—	°
N	Normal force	—	N
F_g	Gravitational force along slope	—	N
F_D	Aerodynamic drag force	—	N
F_{rr}	Rolling resistance force	—	N
F_E	Engine force	—	N
v	Velocity	—	m/s
a	Acceleration	—	m/s^2
t	Time	—	s
P_{true}	Effective engine power	—	W
$P_{\text{available}}$	Available engine power	—	W
T_p	Throttle position	0-1	—
C_D	Drag coefficient	0.321	—
C_{rr}	Rolling resistance coefficient	0.01	—
ρ	Air density	1.225	kg/m^3
A	Frontal area of vehicle	2.15	m^2

Table 1: Variables used in the vehicle dynamics model. Values taken from[8].

By using an adapted secant method initialised with $\alpha_0 = 0.1$ and $\alpha_1 = 1$ the following equation is used to iterate towards the optimal value of alpha.

$$\alpha_{k+1} = \alpha_k - \beta f(\alpha_k)\frac{\alpha_k - \alpha_{k-1}}{f(\alpha_k) - f(\alpha_{k-1})} \tag{2.15}$$

That iterates until $|f(\alpha_{k+1})| < \epsilon$ where ϵ is the tolerance which is equal to 10^{-3}. The parameter β is a damping factor introduced to make sure the secant method converges.

2.5 External optimiser

The external optimiser adjusts the throttle profile to minimise energy consumption which is calculated as:

$$E = \sum P_{true}\Delta t \tag{2.16}$$

To find the optimal throttle profile a Nelder-Mead algorithm is used. The Nelder-Mead method works by evaluating the energy usage at multiple points in forming a shape called a simplex. The simplex is then moved and reshaped by reflecting, expanding, or contracting around the search space to find a point that returns a lower value of the function. Then over time the simplex converges towards the minimum.

The parameters that the Nelder-Mead algorithm is optimising are the throttle input values for each segment of the journey. These throttle values can range from 0% to 100%, where 100% corresponds to full throttle, meaning 100% of the available engine power at that moment. The available engine power is not fixed; it depends on the RPM at each point in time, which is determined by the car's velocity and selected gear. Therefore, the optimiser is selecting how much of the available power to use in each segment, balancing energy efficiency with the requirement to meet the target average speed.

The reason the Nelder-Mead method was used is that it works well for multi dimensional,non linear problems whilst a method such as the secant is good for single variable root finding.

3 Results

A series of simulations were run to determine the optimal throttle profile for a 2017 Ford fiesta that minimises energy usage over a journey. In the simulated journeys the road's gradient was varied to see how this affects the driving behaviour.

The total length of the journey was set to 1km with a time constraint of 60s. Then using equation (2.12) this results in a target velocity of 16.67 m/s (equivalent to 60km/h). This is true for all of the following scenarios. To calculate the energy saving the equation to find the energy saving is given by:

$$\text{Energy Saving} = \frac{u_{flat}(x) - u_{optimal}(x)}{u_{flat}(x)} \times 100 \tag{3.1}$$

This equation quantifies how much energy is conserved by using the optimal throttle profile, $u_{optimal}(x)$, in comparison with a constant throttle profile $u_{flat}(x)$.

3.1 Flat road profile

For the flat road profile, depicted in Figure 1a), there is no gravitational force acting on the vehicle. The throttle profile shown in Figure 5 isn't uniform. It has an initial peak at the start of the journey where the throttle is set to the maximum value, resulting in a rapid increase in the vehicle's velocity. After this, the throttle remains stable at around 0.6 before dropping and peaking back up again at around 500m. This is followed by another drop and a final increase near 900m. For a flat road,the optimal throttle profile consists of alternating peaks and troughs, suggesting a fluctuating input strategy rather than constant acceleration. This approach was found to be more energy efficient, achieving an energy saving of 25.50% in comparison to a constant throttle strategy.

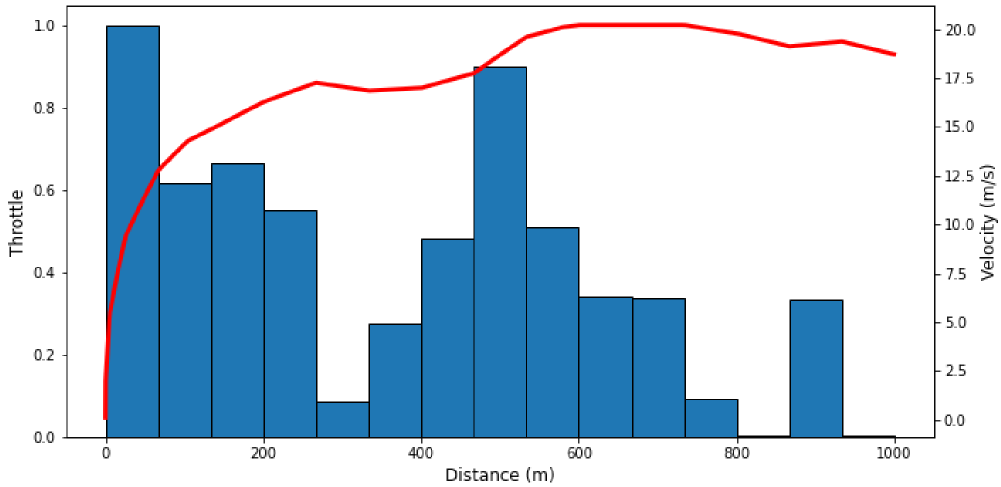

Figure 5: The optimal throttle profile and speed over a 1 km flat road divided into 15 segments: blue bars show the normalized throttle level per segment, and the red line shows the corresponding vehicle velocity (m/s).

3.2 Downhill road profile

To model a realistic driving scenario along a downhill the road profile in Figure 1 b.) was used, this means the gravitational force acts in the same direction as the vehicle's motion. The throttle profile shown in Figure 6 is more front loaded than the flat road scenario. There is a high initial throttle input, with maximum values of throttle input for the first 200m, which brings the vehicle up to speed quickly. After this, the throttle profile has several stretches of zero throttle input, which is where the car is coasting. There is a brief increase in throttle just before 800m, but the reliance on the throttle in the second half of the journey is significantly reduced. The energy saving going downhill was found to be 38.72%

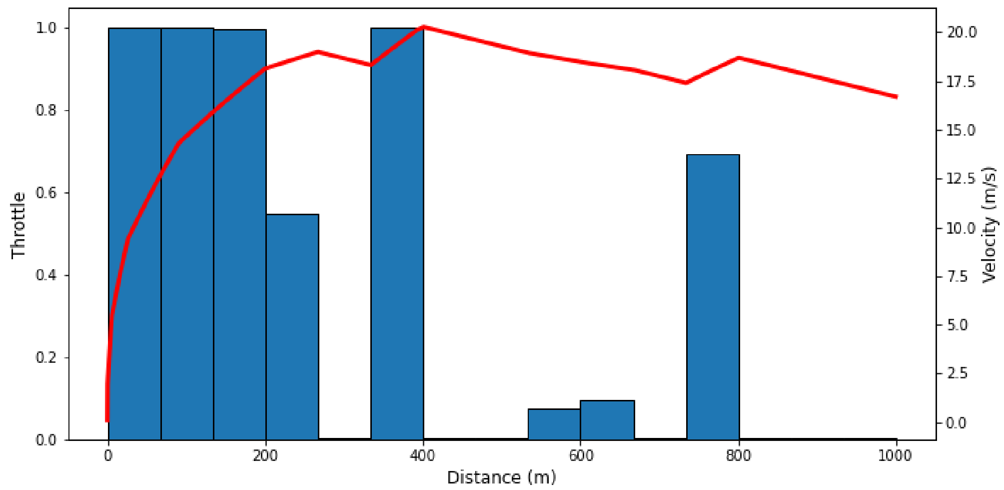

Figure 6: The optimal throttle profile and speed over a 1 km completely downhill road divided into 15 segments: blue bars show the normalized throttle level per segment, and the red line shows the corresponding vehicle velocity (m/s).

3.3 Uphill road profile

For an uphill road profile, as illustrated in Figure 1c.), the gravitational force acts against the vehicle's motion. There is a high throttle at the start which causes the vehicle to accelerate quickly from rest. Then as speed climbs, less throttle is needed so the throttle slowly tapers off. The speed plateaus at around 21 m/s, meaning the vehicle is cruising uphill. This approach leads to an energy saving of 9.29%.

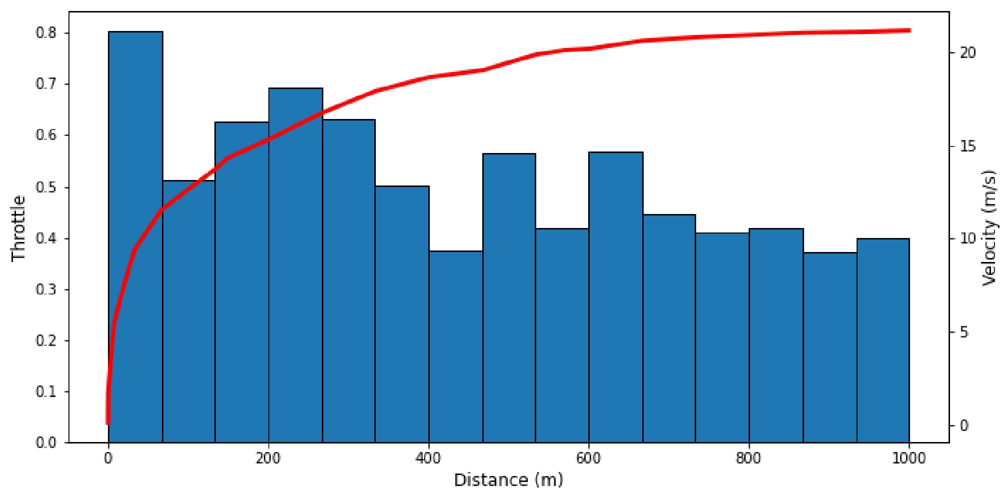

Figure 7: The optimal throttle profile and speed over a 1 km completely uphill road divided into 15 segments: blue bars show the normalized throttle level per segment, and the red line shows the corresponding vehicle velocity (m/s).

3.4 Varied road profiles

For this throttle profile the road profile used is shown in Figure 1 d.). The throttle profile starts with a high input of throttle on the flat section. This gets the vehicle up to a cruising speed. In the downhill section little to no throttle is used, starting a period of coasting. Finally, on the last flat section the throttle values start to peak up to 0.4 causing the velocity to increase. The throttle profile found for this road profile leads to an energy saving of 28.09%.

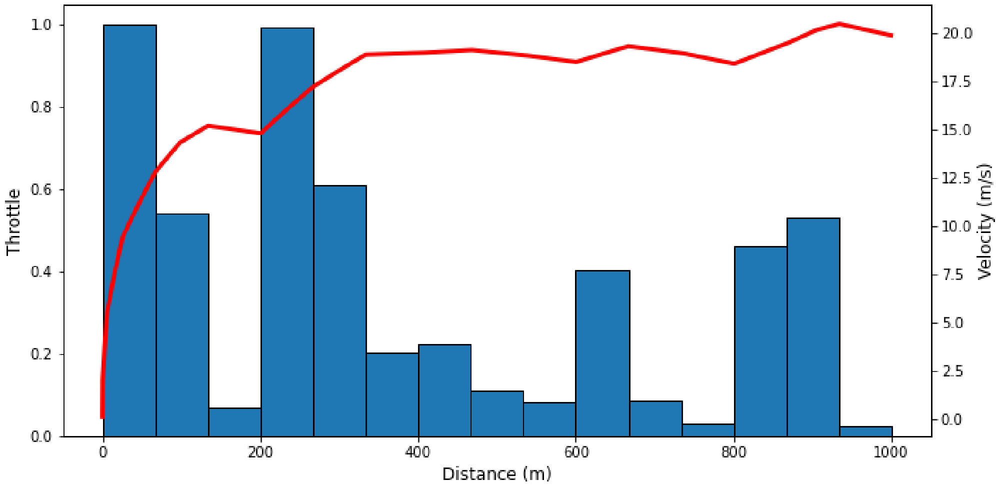

Figure 8: The optimal throttle profile and speed over a 1 km road based of Figure 1.d) The throttle profile has been divided into 15 segments,shown as blue bars representing the throttle levels, while the red line indicates the corresponding vehicle speed(m/s).

The throttle profile for the road profile shown in Figure 1 e.) has very high throttle input for the first flat section. Then for the uphill section there is flat throttle followed by a drop in throttle usage to near zero then it peaks up again just before 600m. For the final flat section it has a peak at around 700m where near max throttle is used then the throttle usage tapers off to zero. This leads to reduction of energy usage of 24.33%.

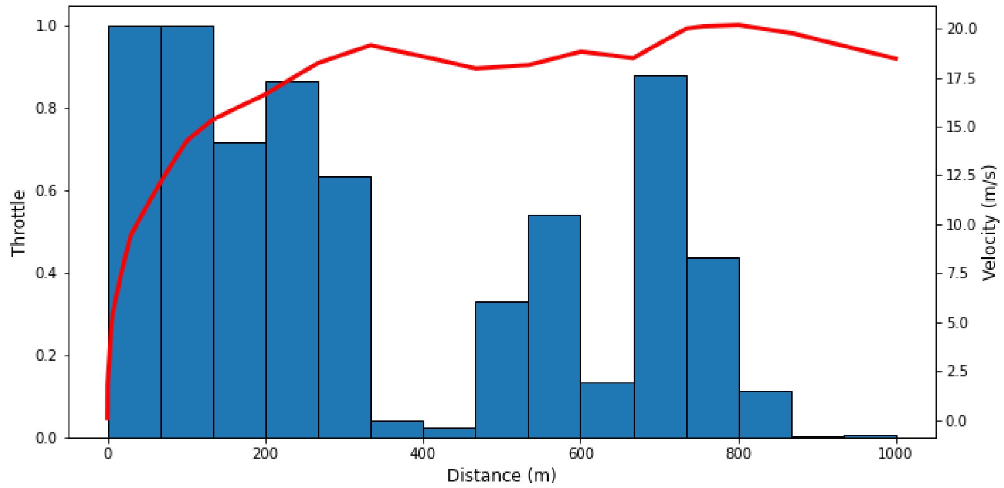

Figure 9: The optimal throttle profile and speed over a 1 km road based of Figure 1.e) The throttle profile has been divided into 15 segments,shown as blue bars representing the throttle levels, while the red line indicates the corresponding vehicle speed(m/s).

3.5 Shift RPM

Figure 10 plots energy usage (kJ) against shift speed (RPM) for a flat road. At a low RPM of 1500, the energy consumption is at 870 kJ. As rpm increases, energy usage steadily decreases, reaching a minimum of 508.32 kJ at 4500 RPM. Overall, the data shows a general trend of decreasing energy consumption with increasing shift RPM, up to a certain point, beyond which a slight rise is observed.

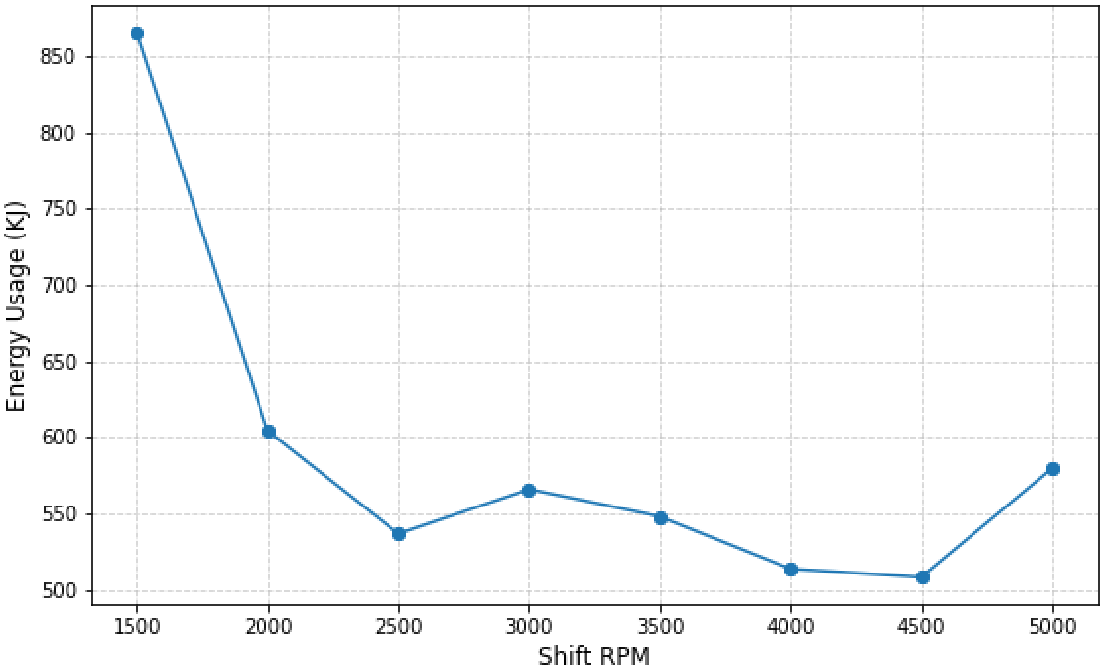

Figure 10: Energy consumption (kJ) vs shift speed (RPM).

3.6 Uncertainty and validation of results

For every simulation run, all the model parameters are held constant. This means that each time the simulation is run for a given scenario, the throttle profile found is identical. This is because finding the optimal throttle is a purely deterministic problem. Therefore, the energy savings quoted represent the mean value with zero standard deviation.

Although the simulation itself is deterministic under fixed inputs, the solution found for the optimal throttle profile can still depend on the optimiser's configuration. Parameters such as the convergence tolerance and the maximum number of iterations can impact the result. This introduces a form of uncertainty not from randomness, but due to the sensitivity of the solution to the optimiser settings.

To further validate the results, a candidate throttle profile obtained from the optimiser was tested by making slightly perturbed neighbouring profiles. It was then found that the neighbouring profiles used less energy, suggesting that the solution was not yet optimal. So, the candidate profile was used as a new starting point. This time, all neighbouring profiles resulted in higher energy usage, confirming that the optimiser had converged to the true minimum.

In addition to the optimiser's settings, the impact of other simulation parameters—such as the time step and the number of throttle segments—was also explored. By varying the time step size, Δt, it was found that a smaller Δt improves accuracy by providing finer time resolution. However, this comes at the cost of increased computational runtime. For this study, a value of $\Delta t = 0.05$ was chosen as a compromise between accuracy and computational efficiency.

The number of throttle segments used to define the throttle profile was also varied. Increasing the number of segments allows the model to more accurately capture throttle behaviour over the course of the journey. However, this also increases the dimensionality and complexity of the optimisation problem, making it more difficult for the optimiser to reliably find the global optimum.

The chosen configuration reflects a balance between solution precision and practical feasibility. A total of 15 throttle segments was selected to provide sufficient resolution while maintaining computational efficiency.

4 Discussion of Results

The results for the optimisation clearly demonstrate that a non-steady throttle profile which adapts to the terrain yields significant energy savings when compared with a constant throttle profile. Across most scenarios, the optimisation process found that throttle profiles which use the Pulse and Glide technique are the most energy efficient driving strategy. This echoes what other literature states as the most effective strategy [9][10].

4.1 Comparison With Other Literature

Studies of eco-driving reported energy savings of 2-25% [2][3] through techniques such as smooth acceleration and minimising idling. The energy saving found for a flat road resulted in a 25.50% energy saving,relative to a constant throttle, which lies at the upper end of the reported energy savings found in [2][3] . More notably, for a downhill road the energy saving increased to 38.72%. This exceeds typical published values highlighting the role gravity plays in enabling extended glide phases.

4.2 Terrain dependence and guidance

The sensitivity of energy savings to an incline is stark: from 38.72% downhill to 25.50% on flat terrain,and down to 9.29% uphill. The energy savings from going uphill are smaller since there is a minimum throttle usage that is needed to prevent the car from going backwards and to counteract the gravitational forces. However a 9.29% reduction still represents a meaningful cut in fuel consumption. For a real world scenario drivers should aim to gain speed before a hill then use a modest amount of throttle and accept a steady climb rather than constantly applying a high level of throttle. Conversely, for a descent, it is optimal to let gravity do a lot of the work and coast until speed drops then provide a pulse which is seen in Figures 5 and 7.

The investigation of RPM at which gear shifting occurs provides insight for drivers on the optimum gear shifting strategy. The shift RPM which used the least energy was found to be 4500 RPM. Having said that, shifting at this rpm will place significant strain on the engine, potentially reducing the vehicle's lifespan. In contrast a shift RPM of 2500 RPM may not be the most energy efficient, but it strikes a balance of reducing energy consumption and minimising mechanical stress making it a more suitable choice for everyday driving.

4.3 Benefits of the current model

The benefits of the current model are the integration of a realistic engine map and manual gear transmission based on real-world data. Also the combination of the optimisers ensures that the time requirement is met while also minimising energy usage, this means we get realistic results.

Another advantage is the exploration of multiple road profiles demonstrating the robustness of the model.

4.4 Limitations of the model

The model currently simplifies most aspects of real world driving. The model doesn't account for traffic interactions, speed limits or stop start scenarios (i.e. junctions or road signs), the optimiser assumes a perfect knowledge of road grade and has no external disturbances. The reality is that the throttle profile would be adjusted to account for surrounding traffic. The model only provides insight on straight roads, it doesn't take into account cornering and as such the need for braking wasn't incorporated into the model, this would shift what the optimum profile looks like.

The uncertainty analysis shows that there is zero variance with fixed parameters, as the optimal throttle profile is a deterministic problem. However, in practice for real world driving, there would be uncertainty dependent on parameters such as weather conditions affecting the value of the rolling resistance coefficient. Additionally vehicle mass will be altered dependent on how many people are in the car and how full the fuel tank is.

To improve realism, future simulations could use more throttle segments. This would allow finer control and better adaptation to varying driving conditions. While it increases optimisation complexity, it is an important step toward more realistic and comprehensive modelling.

4.5 Directions for future work

To bridge the gap between the model and real-world driving, on-road experiments could be conducted using a data logger or an instrumented vehicle to record live data. This would allow the model to be tested under real conditions but the vehicle dynamics would also need to be updated to account for situations where the vehicle is following another car. The methods used could be extended to hybrid and electric powertrains because that currently seems the likely future of the automobile sector. Finally coupling the current model with a route planning tool could provide drivers with a tool that optimises both path taken and the driving strategy simultaneously to maximise fuel economy.

5 Conclusions

The purpose of this project was to develop a model to investigate how driving strategies can influence fuel consumption for a passenger car with a petrol engine. By combining vehicle dynamics, gear shifting, and engine performance data, as well as optimisation routines, the model was able to find the optimal throttle profiles for a variety of road terrains that minimises energy usage while still meeting a realistic time constraint.

The results highlighted that adapting the throttle profile according to the road terrain leads to a decrease in fuel usage compared to a flat throttle level. Across different terrains, the optimal throttle profile resembled a pulse-and-glide technique. The most significant reduction in fuel consumption, 38.72%, occurred when driving downhill, while driving uphill led to a meaningful reduction of 9.29%. These results are consistent with current literature on this topic and highlight the importance of road terrain when maximising fuel economy.

While the model was built with a number of simplifications such as no traffic interaction,braking events and perfect knowledge of road gradient it provided a clear framework to understand the potential benefits of eco driving methods. In reality, road junctions and the presence of other vehicles would cause adjustments to be made to the driving style and limit the achievable savings.

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