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DEVELOPMENT OF A VEHICLE LONGITUDINAL PERFORMANCE SIMULATOR

A PROJECT REPORT

DE-XLI (DME)

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ABSTRACT

Analyzing a vehicle’s longitudinal performance during motion and studying it in terms of the engine’s output is one way of enhancing fuel efficiency of a car. The way a person drives their vehicle can affect its fuel consumption greatly. This is where fuel efficient driving techniques come in to ensure eco-friendly driving practices. Drivers that are trained for ideal vehicle longitudinal performance can get much better fuel efficiency from their cars than regular people with no such training or knowhow. Research suggests a considerable amount of fuel is wasted due to negligence in driving methods in the form of heat and other wastes. Errors like excessive acceleration or braking can cause lower average efficiency of the car. These variables depend on the driver and with proper training and feedback, one can minimize these wastes. It would be a waste itself to undergo extensive training in actual cars which involves wastage of fuel as well as other risks and hazards. A simulated environment on the other hand provides a much safer and economical solution to this problem. By eliminating irrelevant factors and forces, we can focus on our desired aspects of the vehicle in motion and evaluate the driver’s ability much more accurately. This is what brought about the idea of a simulated car used to evaluate and teach fuel efficient driving methods to a driver. This report gives an insight on the key aspects of the project, the problem that is being dealt with, and the approach that is being taken to solve it.

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F_D	force of aerodynamic drag acting on the vehicle
C_D	coefficient of drag
A	frontal area of the vehicle
ρ	density of the air.
V	velocity of the vehicle.
F_y	lateral force (sideways force) generated by the tire.
α	slip angle, which angle between the tire's heading direction and the direction of travel.
$B, C, D,$ E	the empirical coefficients that depend on the tire and its characteristics. These coefficients are determined through experimental testing and parameter fitting.
F_z	vertical load on the tire,
κ	slip ratio or slip angle,
γ	is another parameter that may represent additional effects.

Chapter 1: Introduction

Efforts to enhance vehicle longitudinal performance while minimizing fuel consumption and emissions are of paramount importance in the development of existing and future vehicles. This project aims at providing a virtual platform for analyzing and simulating longitudinal performance of vehicles and focus on improving the efficiency of vehicles and driving patterns. Our simulator consists of a hardware rig fitted with Logitech hardware for driver input. The simulation is designed in Unity 3D software with accurate vehicle dynamics and engine parameters. The driving patterns of the driver including the gear shifting strategies and braking/accelerating methods are recorded during the simulation. This data is used to calculate the fuel consumption of the drive cycle. Moreover, the simulator provides feedback about the mistakes made during driving in terms of fuel wasted and how they can be remedied. The simulator can serve as a teaching tool for efficient driving methods, by giving real-time feedback during the simulation for cues like gear changes and throttle positions. The goal is to drive the car as economically as possible, and the simulator provides a virtual environment to assess and train drivers in this area. To further validate our findings, and to study the engine virtually, a MATLAB engine model has been integrated with the unity software which allows us to compare any given drive cycle with ideal driving methods and obtain data like fuel consumption, engine performance, etc. The grouping of these tools in the simulator not only lets us measure fuel consumption of vehicles virtually but can also be used to design vehicles for better performance and optimization [1].

1.1. Literature Review

The enhancement of longitudinal performance of a vehicle without harming vehicle performance remains a top priority in the development of existing and future vehicles. This means that any technical or lawful measurement contributing directly or indirectly to vehicle energy savings must be exploited. Variations in vehicle fuel consumption and emissions are usually associated with changes in cruise speed, driver acceleration aggressiveness, and road grade. Physically and empirically based methods are usually considered in modelling fuel consumption and emissions. An example of the former is the physical emissions rate estimator (PERE), which uses vehicle parameters and second-by-second driving traces as inputs and estimates second-by-second fuel consumption rates. The empirically based modal is exemplified by the motor vehicle emission simulator

(MOVES) to estimate energy consumption for vehicles. Because of the high number of possibilities, we limit this research to study the results of the influence of the parameters intervening in various vehicle resistances and in the transmission. By a reasonable variation of the selected parameters we manifest the tendencies and the limits of fuel economy of a standard vehicle. To study the influence of various selected parameters on the fuel consumption, a software tool is developed allowing simulation under any vehicle operating conditions (vehicle moving at constant speed or according to a known driving cycle) and which determines the fuel consumption. Another system called "virtual and real simulator (V&R-S)" for engine development was devised in a paper by Koji Shirota, Fumihiko Baba and Masafumi Horikoshi. The system created dynamic load of drivetrain, wheel, body, and road with the virtual vehicle model. However, it was effective only for engine test bench level diagnostics. Our simulator provides a complete vehicle model for simulating its performance and can act as a chassis dynamometer for any virtual engine [2].

The simulator also gives continuous feedback regarding the measures that should be achieved for the longitudinal performance of the vehicle. Furthermore, the aim of this project is to integrate the simulator with hardware so that the results of the study can be rationally authenticated.

1.2. Motivation

Different kinds of vehicle simulators serve different purposes and are being used all around us. The purpose of our longitudinal performance simulator is to study and enhance fuel efficiency. The basic motive behind making this fuel-efficient simulator is that it would help the user to learn how to make their rides more efficient in terms of fuel. In Pakistan, fuel prices are becoming a major crisis. Drivers should learn fuel efficient driving techniques for economic and environment friendly driving. A simulated environment is useful because there are no chances of accidents during learning over simulator. Moreover, in real life it can be very costly to train a new driver on the training of fuel efficiency as it will require a lot of fuel to train the driver professionally. Analyzing our desired parameters is much easier when irrelevant variables can be factored out in a simulator [3].

1.3. Sustainable Development Goal

Our project is aimed to meet SDG or Sustainable Development Goal 12 which aims to ensure sustainable consumption and production patterns. By focusing on enhancing vehicle longitudinal performance and minimizing fuel consumption, the project promotes sustainable consumption patterns. Improved fuel efficiency directly contributes to reducing resource consumption and greenhouse gas emissions, aligning with the goals of SDG 12.

1.4. Structure

Following is the structure of the report ahead:

- Chapter 2 deals with identifying a gear shifting strategy for better fuel economy.
- Chapter 3 deals with the process of making the simulator in Unity 3D software.
- Chapters 4 and 5 deal with the dynamics of the vehicle so that the model in the simulator can have realistic physical attributes.
- Chapter 6 deals with the major concepts in vehicle longitudinal performance.
- Chapter 7 deals with the process of data acquisition and processing from unity.
- Chapter 8 deals with the hardware tools used for giving input and their integration with the software.
- Chapter 9 deals with processes involved in fabrication of simulator kit.
- Chapter 10 deals with the limitation faced during the project.
- Chapter 11 deals with applications of the project in the real world and automotive industry.
- Chapter 12 deals with future prospects and plans for the idea and gives a conclusion of the project.

Chapter 2: Gear Scheduling

Of all the factors that affect fuel economy of a conventional passenger vehicle, the gear shifting schedule of the driver is of primary importance. It was significant in our case because it is greatly dependent on the driver of the vehicle and varies for each person. Unlike other vehicle and engine parameters affecting fuel economy, gear scheduling cannot be pre-programmed in a simulator designed for a manual transmission vehicle. This data is recorded during the simulation. To optimize this factor, we need to train the driver on an optimum gear shifting schedule devised for minimum fuel consumption and better engine performance. Our aim was to include a guide in our simulator that would compare any driver's gear shifting methods with an ideal one set as a benchmark. This would provide insight about how much fuel has been wasted due to inappropriate gear shifting of the driver and how much room there is for improvement in the driving methods of that person. For this, we need to understand what gear scheduling is, and how it is designed for different purposes like maximum engine power output or most economic driving method.

2.1. Optimal Gear Shift Strategies for Fuel Economy

Gear scheduling is the process of choosing the correct gear for the speed and conditions of the road. When driving, it is important to use the suitable gear to avoid wasting fuel. For example, driving in a high gear at low speeds can cause the engine to work harder than necessary, leading to increased fuel consumption. Similarly, using a low gear while going at very high speeds can damage the engine [4]. Therefore, keeping our basic purpose of providing a platform for training drivers in fuel efficient driving methods, we need some logic for deriving a gear schedule based on real vehicle parameters. An ideal gear schedule would consider vehicle speed, engine speed, drag forces, total load, and other parameters and suggest the optimal gear for any given set of conditions. This schedule can then be programmed into the simulator and used to assist drivers during the simulation. This can be done in the form of live feedback during the virtual drive, or at the end of a drive cycle in the form of total statistics of the simulation.

One of the key benefits of gear scheduling is that it helps to reduce fuel consumption. When the engine is working efficiently, it uses less fuel, which can result in significant savings over time. Studies have shown that proper gear scheduling can improve fuel efficiency by up to 15%. This means that we can reduce fuel costs in our daily lives by training in fuel-optimal gear shifting schedules. Another benefit of gear scheduling is that it can help to reduce wear and tear on the engine. When the engine is working too hard, it can cause damage to the components, which can lead to costly repairs. By using the right gear, the engine can operate at its optimal level, reducing the risk of damage and prolonging the lifespan of the vehicle. Proper gear scheduling can also lead to a smoother driving experience. When the engine is working efficiently, it produces less noise and vibration, making for a more comfortable ride. This can be especially important for long journeys, where driver fatigue can be a real issue. By reducing the strain on the engine, gear scheduling can help to make driving more enjoyable and less tiring.

2.2. Designing A Gear Schedule

Shifting gears at the appropriate time while driving can help increase efficiency and reduce fuel consumption. But how do we know this appropriate time? For this, we need to define some set parameters that directly affect the ideal shifting point of any gear. Studying these factors will provide the basic principles for when to upshift or downshift any gear while wasting as little fuel as possible and keeping other losses to a minimum as well. In this section we shall look at the primary factors on which the gear scheduling depends and their trends.

2.2.1. Vehicle Speed

The speed of the vehicle as shown by the speedometer is one of the most obvious indicators for changing gears while driving. Shifting points are often determined by the speed at which one is driving. The general trend is that as one accelerates, the vehicle needs to be shifted to higher gears to match the speed of the vehicle. The exact speed at which any specific gear needs to be upshifted or downshifted cannot be determined by the speed alone and varies for different vehicles having different gear ratios. To make things easier for the driver, we can derive the gear schedule in terms of speed of the vehicle and alert the driver to upshift or downshift any gear as soon as a certain threshold is crossed. Of course, we need to check whether the vehicle is accelerating or decelerating and suggest the next gear accordingly. The cue given to the driver at any specific speed is not based on vehicle speed alone, rather it is a result of the simulation. The simulator is designed to process all the parameters involved in the gear scheduling and calculate the optimal gear for those conditions. The result is displayed on the screen of the simulator if it does not match the current gear that the virtual vehicle is in at that moment [5].

2.2.2. Engine RPM

Engine RPM refers to Revolutions Per Minute of the engine crankshaft. It is an important parameter in gear scheduling and determining gear shifting points. Each gear has an ideal range of engine RPM in which the engine provides maximum power and wastes least amount of fuel. The upper end of the range uses more fuel for more power, whereas the lower end is used for economic driving but at less than max power. This range of RPM must not be crossed and can be maintained by shifting gears accordingly. Usually the RPM is maintained between 2000 and 3000. If it is about to go above this range, the vehicle needs to be upshifted, and if the RPM falls below this range, the gear must be reduced or downshifted. The simulator has a realistic tachometer in the dashboard that gives live reading of the virtual vehicle's engine RPM. This reading can be used to determine the gear shifting points during the simulation.

The chart given below can be used to determine the speed range for each gear in which engine RPM stays between 2000 and 3000. The simulator tells the driver to upshift or downshift as soon as vehicle leaves that speed range.

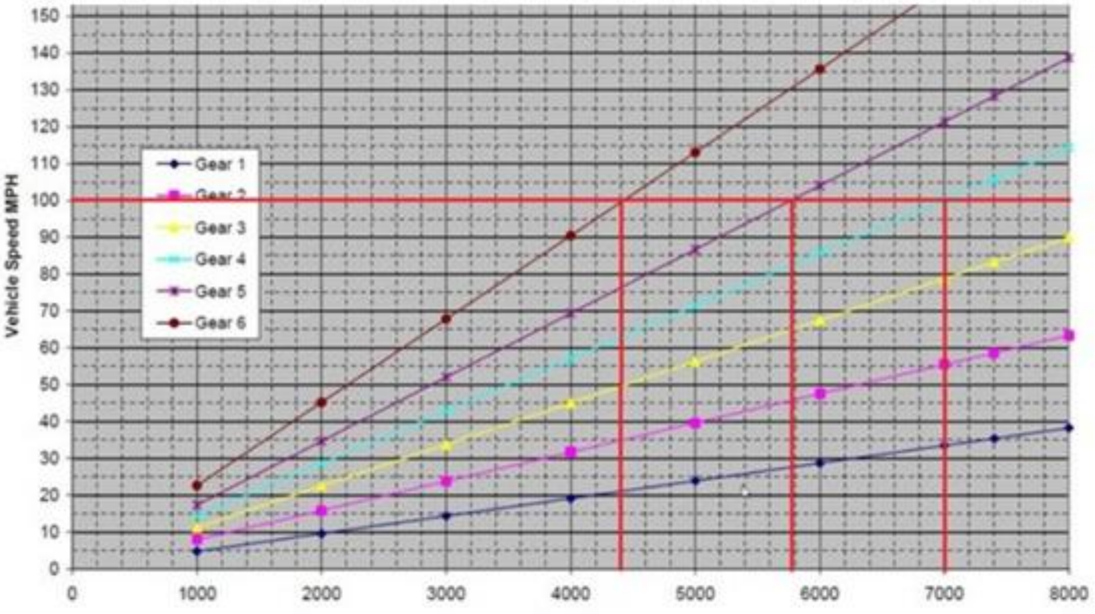


Figure 2.1: Vehicle Speed vs Engine RPM Relation

This describes the variable load on the engine when the vehicle is being driven. Apart from the weight of the vehicle, which is usually fixed, there are other loads acting on a vehicle that can vary. These include aerodynamic drag, extra cargo, inclinations in the road, etc. The shifting points of gears do not remain the same after these load adjustments and must be catered for accordingly. Usually a bigger load means that more power is required to move the vehicle and it takes longer to reach higher speeds. Gears are changed later than usual in these conditions. Therefore, in large trucks the first gear is only used when the truck is loaded with heavy cargo and is not required in the absence of heavy loads [6]. The simulator provides users with the option of changing vehicle loads to exactly simulate their driving conditions and calculate the gear shifting schedule accordingly. *Figure 2.2* below demonstrates the general relation between engine load and RPM in terms of fuel efficiency.

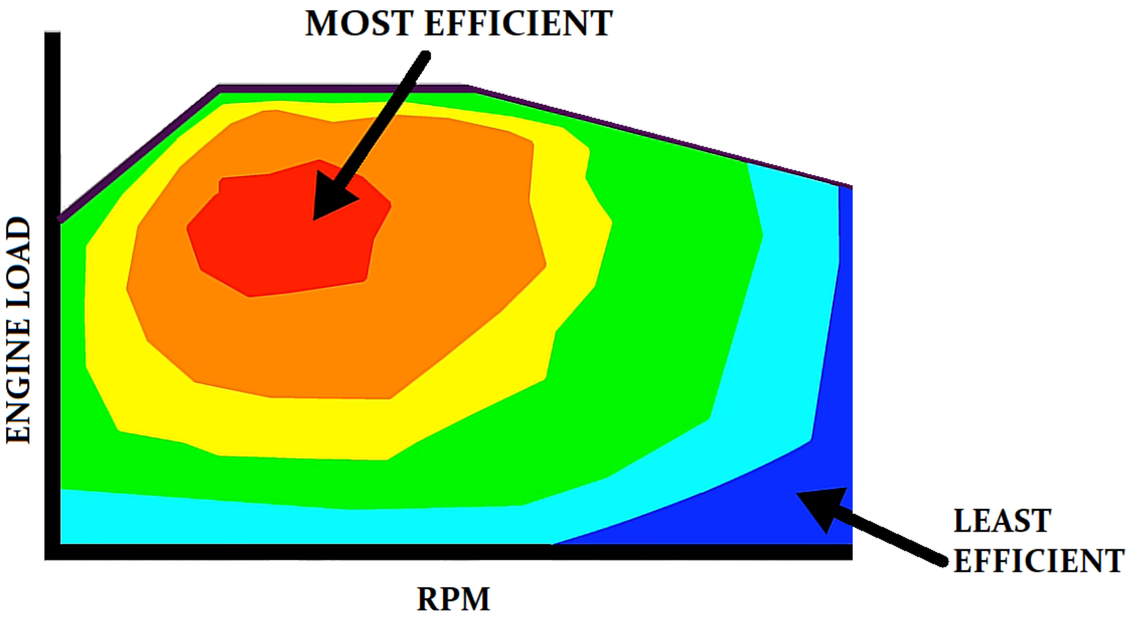


Figure 2.2: Engine Load vs Engine RPM chart

2.2.4. Throttle Position

Throttle position is also an important factor in determining the gear shifting point in a manual car. This refers to how much the accelerator pedal is depressed from its extreme position. The throttle position affects the engine's power output and RPM, which in turn can impact the ideal shifting points. Here's how throttle position can influence gear shifting and fuel economy:

Wide-open throttle: When the accelerator pedal is pressed fully (wide-open throttle), the engine produces maximum power. In this scenario, gears should be upshifted at relatively higher RPMs. Shifting at higher RPMs allows you to take advantage of the engine's power band and maintain strong acceleration.

Partial throttle: In the case of partial throttle, the engine is operating at a lower power output. In this scenario, the relatively lower engine power must be matched by appropriate gears and hence gears are shifted at lower RPMs. Shifting at lower RPMs can contribute to better fuel efficiency by keeping the engine operating within its efficient range.

This phenomenon can be demonstrated in the figure below which provides a basic idea of how gear shifting is done at different speeds in relation to throttle positions. The

100% position on the x-axis represents wide-open throttle, and less than 100 is partial throttle. For any given throttle position, and a gear number, there is a specific speed at which the gear should be upshifted or downshifted for ideal performance. It can be seen that the vehicle is generally in a higher gear in partial throttle case for any specific speed as compared to wide-open throttle case. This agrees with the reasoning stated above.

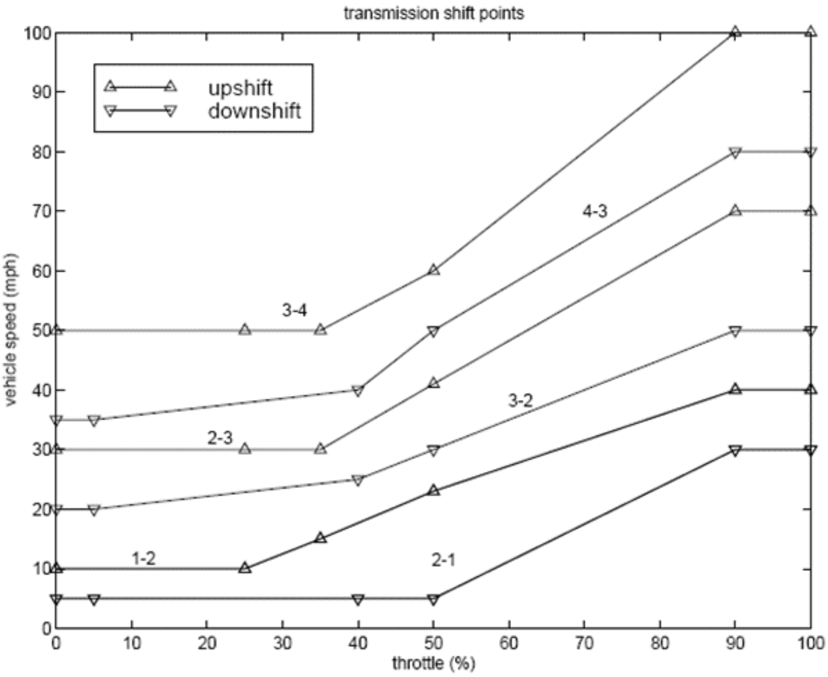


Figure 2.3: Gear shifting points for partial and wide-open throttle

Economy driving: In our case, we are primarily focusing on maximizing fuel efficiency. This can be done by easing up on the accelerator pedal and maintaining partial throttle positions as well as lower RPMs. This practice ensures reduction in fuel consumption. It is important to find a balance between vehicle speed, engine RPM, engine load, throttle position, and the power demands of the vehicle being driven. Smooth and gradual throttle inputs, along with shifting at appropriate RPMs, can help optimize fuel efficiency and performance. To be able to devise an ideal gear shifting strategy, we need to analyze all these factors concurrently. Studying a vehicle's characteristics and experimenting with different driving techniques can help determine the most efficient shifting points for a fuel economic gear schedule [7].

Chapter 3: Unity 3D Simulator

3.1. Prepare the environment:

The environment in Unity 3D refers to the virtual world or surroundings that are created for a game or application. It includes elements such as terrain, buildings, objects, roads, textures, lighting, and effects that form the backdrop and perspective for the gameplay.

The environment plays a crucial role in Unity 3D as it sets the stage for the game, providing realistic scenery that enhances immersion by creating a believable and engaging virtual world. The environment helps to establish the visual aesthetics, atmosphere, and mood of the experience due to its realism and authenticity.

The first step towards building a driving simulator is to find a good environment that gives a realistic appeal to the driver. Given the main purpose of our simulator is to study the effects of driving behavior on longitudinal performance, one crucial prerequisite for the selection of an environment is the inclusion of a comprehensive urban driving network that seamlessly integrates both city roads and highways, instead of a simplistic arrangement of straight roads without any turns.

3.1.1. Create Buildings: -

In the foreground there is a large building with many windows and balconies, as well as several smaller buildings surrounding it. In the distant background, additional towering buildings contribute to the overall urban design. There are some other structures such as garages and parking lots scattered throughout the scene. Together, these components pleasantly blend to form a distinctive and visually captivating representation of the virtual cityscape.

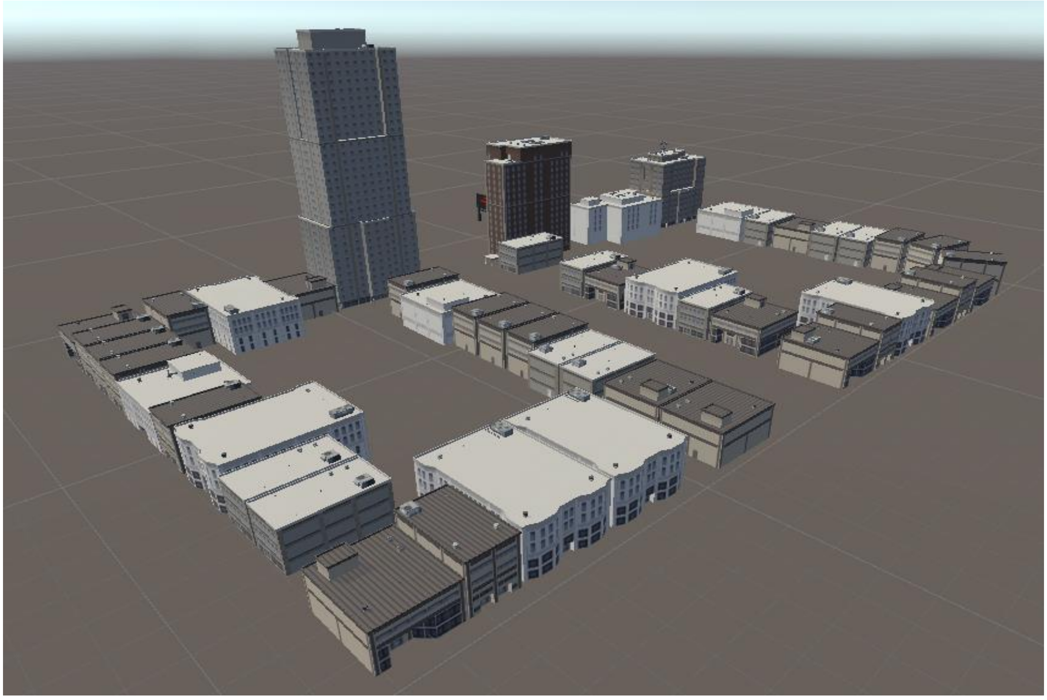


Figure 3.1: Buildings included in Environment

3.1.2. <u>Create Ground Surface: -</u>

Ground surface has been created surrounding the buildings, divided into four distinct sections. The predominant area is covered in sand, forming the base around the driving tracks. In addition to the sand section, there are two concrete areas and a designated grassy patch. This division of the ground into different materials adds visual diversity and enhances the overall realism of the environment.

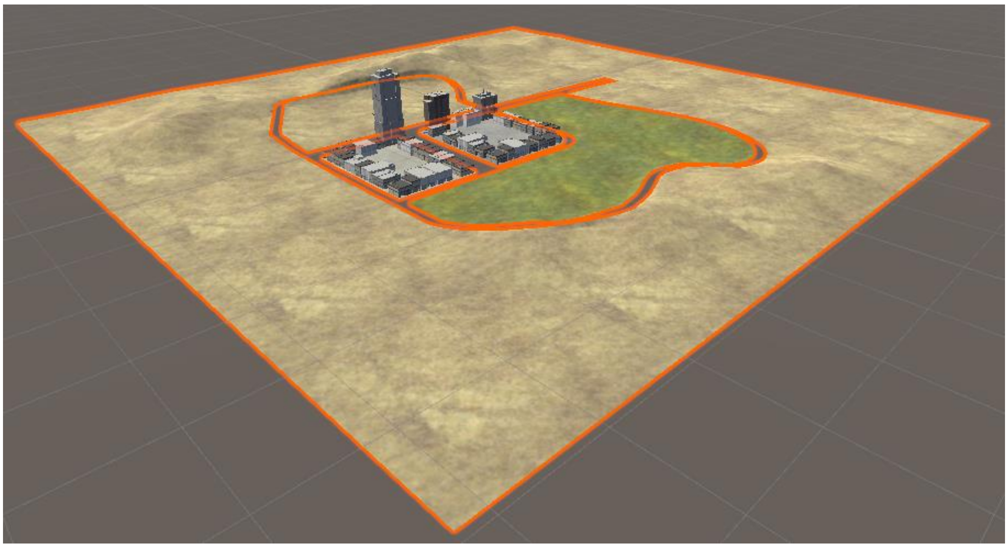


Figure 3.2: Ground Surface

3.1.3. City Driving Circuit:

The scenario has a highway to provide a different driving experience from the city driving circuit. Unlike the urban roadways, this highway offers a distinctive and unique driving path. By introducing faster speeds, more straightaways, and a different visual style from the city driving track, it diversifies the entire experience.

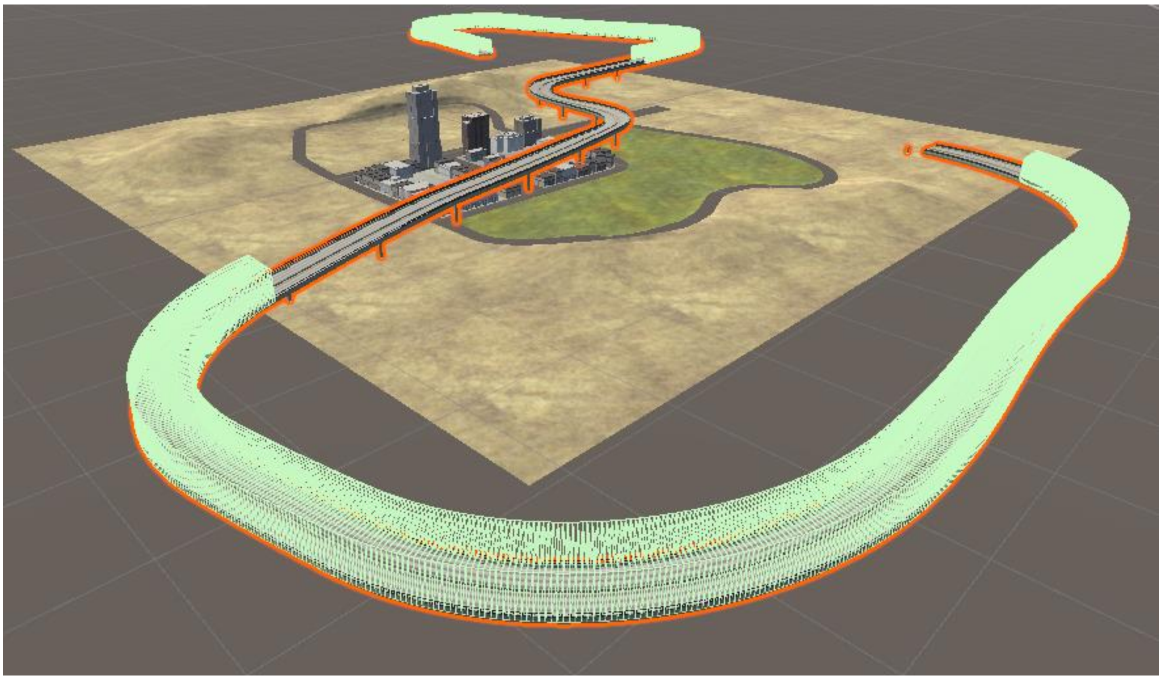


Figure 3.3: Highways

The track's roads have been neatly incorporated, enclosing the structures, and linking the city driving track to the highway. Vehicles use these highways as their routes through the virtual environment. They create a direct connection between the city driving track and the highway in addition to offering a continuous route around the buildings. This integration improves the overall accessibility and flow of the driving experience by enabling seamless changes between various track segments.

Figure 3.4: Track Roads

3.1.4. Immersive and Diverse Urban Environment:

The driving route is designed to be user-friendly, with no complex routes for the driver to memorize. After starting from the initial point, the driver will encounter a straightforward road. Upon reaching an intersection further down the road, they will have two options for turns. Taking a left or right turn at this intersection will lead them to a city driving track. However, if the driver continues straight, they will eventually come across another intersection, where they can again choose to turn left or right, leading them to a highway driving track.

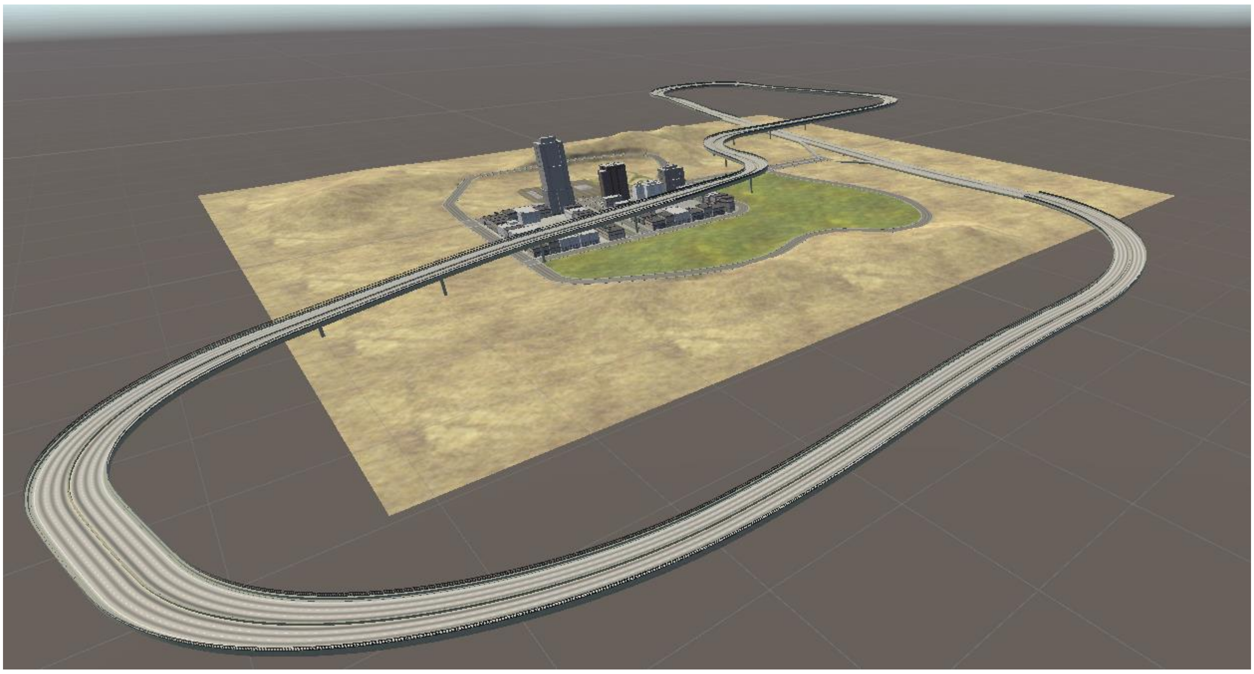


Figure 3.5: Urban Environment

3.2. Create the vehicle:

The car's intricate design incorporates a variety of necessary parts to guarantee both its functionality and aesthetic appeal. Starting with the exterior, we have the bonnet, which protects and provides access to the engine's interior while also providing maintenance. The boot, which is towards the back and provides storage for items, frequently has a boot light to improve visibility. In crashes, the front bumper acts as a barrier to protect the underlying structure by absorbing impact. The rear bumper functions similarly as a protective shield to reduce damage in the event of a rear-end collision. The chassis is the bedrock of the vehicle, providing structural support and acting as a base for attaching other parts.

Any vehicle's doors, which are an essential component, allow the driver and passengers access. Door glasses serve as a barrier from the weather in addition to providing transparency for visibility. For easy entry and exit, the door handles provide a way to open and close the doors.

On both sides of the automobile, wing mirrors give the driver essential rear-view visibility. They enable surveillance of oncoming traffic and support safe lane changes. The car's engine, also known as its "heart" produces power and moves the car forward. Gases released during combustion are expelled through exhaust pipes, which improves engine performance and lowers pollutants.

The front grill ensures effective cooling by facilitating airflow to the engine compartment in addition to serving as a decorative element. Headlights provide vision of the road in front of them during bad weather or at night. Wipers are necessary to keep a clear windscreen by clearing away rain, snow, or other debris.

The steering wheel gives the driver control over the direction of the vehicle, enabling safe navigation. There are four wheels that contact the ground and have tires on them to give traction, stability, and easy maneuverability. The driving experience is improved by wheel colliders, a physics feature in Unity that allows for realistic interactions between the wheels and the virtual ground.

These parts come together to create a whole car that combines utility, safety, and aesthetics. Their thoughtful integration results in a well-designed, fully functional car that can provide a safe and satisfying driving experience.

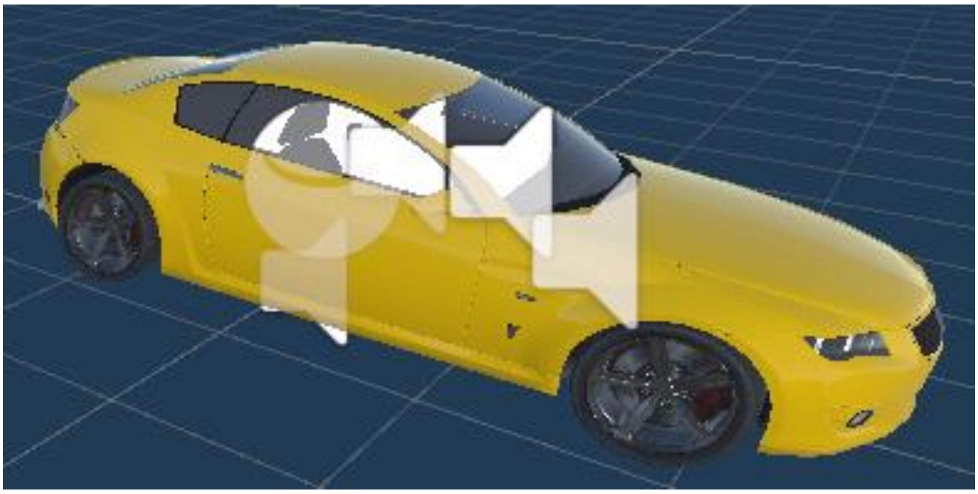


Figure 3.6: Car Chassis

Chapter 4: Vehicle Physics I

4.1. Mass:

The mass of vehicles affects the longitudinal performance parameters such as fuel economy. This mass represents the total mass of the vehicle in driving conditions as if we put it on a scale, including driver, fuel, wheels, etc.

Engine must work harder to move a heavier vehicle to produce more power to overcome the increased inertia and friction caused by the mass leading to the increased engine load and hence higher fuel consumption [8].

Mass also affects the aerodynamic drag and, the aerodynamic drag increases with increase in mass but obviously the shape and design of vehicle, the angle of windshield and presence of aerodynamic features like spoilers or air dams play a significant role. In our car we have air dams (bumpers), but spoilers are not included.

While there is no direct mathematical relationship linking mass to fuel consumption, but just for literature purposes if the drive cycle and all other parameters are assumed to be constant (although not realistic), the fuel consumption is increased up to 0.95% by increasing 100kg mass.

The Toyota Yaris is a lightweight car with a curb weight of 1105 kg. The entire mass would be around 1171 kg if we included the average weight of male Pakistanis, which is 66 kg, to the curb weight.

We estimate the Toyota Yaris' overall mass to be 1171 kg by adding the average male weight of Pakistanis. It is critical to remember that this computation is only an approximate estimate, and that individual vehicle weights may change based on particular model variations and optional extras [9].

4.2. Driveline:

In the context of drivelines found in many cars in Pakistan, including the Toyota Yaris, it is common to have a single driven axle, which is typically the front axle. A driven axle refers to an axle that receives power from the engine and transfers it to the wheels to propel the vehicle.

4.3. Transmission Efficiency:

Transmission efficiency refers to the effectiveness with which power is transmitted through the vehicle's transmission system. The values range from 0 to 1, representing the ratio of the power output at the transmission's output shaft to the power input at the transmission's input shaft [10].

The transmission helps determine the engine RPM at which the engine operates by selecting the appropriate gear ratio. An efficient transmission can enable efficient and more precise gear shifts. A more efficient transmission system results in minimizing power losses and therefore there is less engine load leading to more fuel efficiency. Similarly, the torque output increases due to efficient transfer of power from engine to wheels. The transmission in Toyota Yaris is 6-speed MT. The efficiency of manual transmission typically ranges from 90% to 95%. As the exact value for Toyota Yaris could not be found, let us assume the value to be 0.925.

4.4. Differential:

There are 5 types of differentials available in Unity 3D editor. Different types of differentials, such as open differentials, limited-slip differentials, locked differentials, etc. offer varying degrees of power distribution and traction control. These differentials cater to specific driving conditions and preferences, providing enhanced performance and safety in various scenarios. Before mentioning the differential used in our vehicle, here is an overview of the five differentials:

4.4.1. Open Differential:

An open differential is the most basic and commonly used type of differential. It allows the drive wheels to rotate at different speeds during turns, promoting smooth control and reducing tire wear. As the power is transferred to the wheels with least resistance, it results in wheel spin and reduced traction on slippery surfaces. Passenger cars mostly use this kind of differential.

4.4.2. Clutch Pack (Limited Slip) Differential:

The mechanism behind the clutch pack or limited slip differential is that it transfers torque from wheel with less traction to wheels with more traction. The advantages include improved traction on slippery or uneven surfaces. Sports cars use this differential, one example is Ford Mustang GT.

4.4.3. Locked Differential:

The locked differential locks the drive wheels together at same speed regardless of traction conditions. This provides maximum torque and traction to wheels but restricts wheels from rotating at different speeds which causes tire scrubbing. Jeeps use this differential, one example is Jeep Wrangler Rubicon,

4.4.4. Viscous Differential:

Fluid based mechanism to transfer torque between drive wheels. A set of plates immersed in a viscous fluid, when one wheel loses traction fluid heats up and transfers torque to wheel with better traction. This is not effective in extreme traction conditions. Audi A4 has used this differential.

4.4.5. Torque Biasing Differential:

Sports cars such as Ford Focus RS have built their own differential which is based on the concept of biasing torque known as “Ford Performance All Wheel Drive with Dynamic Torque Vectoring”. This system enhances traction, stability, and cornering capabilities.

The word traction has been used several times in discussing the types of differentials, what is traction?

Traction is the friction between a drive wheel and road surface. If you lose traction, you lose the road grip. Traction can be referred to as useful friction. In case there is no friction between road and tires, the tire will spin about its own axis.

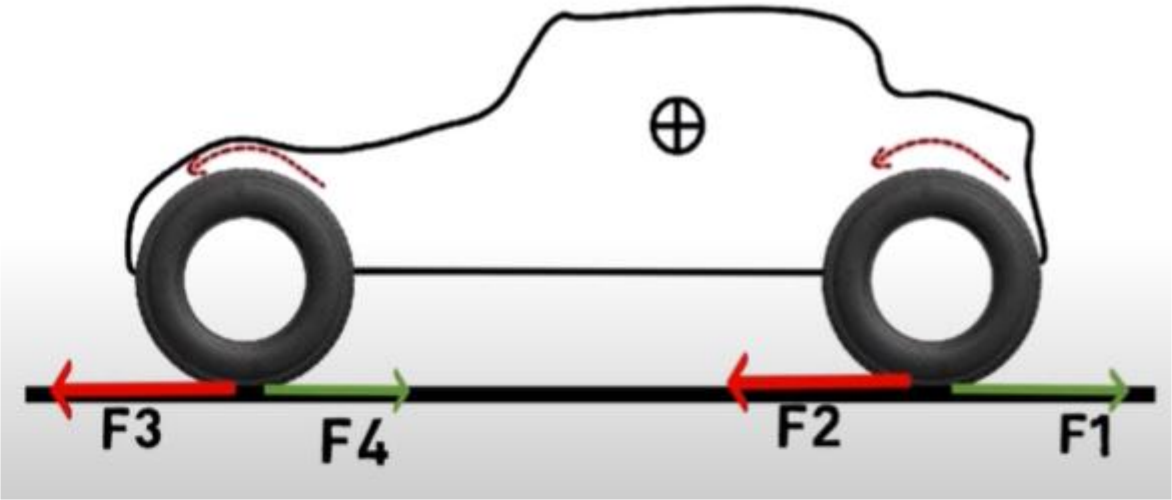


Figure 4.1: Tractive Force

F_2 and F_3 are the tractive forces here. In the case of all four-wheel drive, both will be called tractive force whereas for rear wheel drive F_2 will be referred as tractive force and for front wheel drive F_3 will be called tractive force.

Traction depends on weight transfer, load, position of center of gravity of vehicle. Traction also increases due to the aerodynamic downforce. Traction is crucial in turning because it directly affects the vehicle's ability to maintain grip and control while navigating a corner. When a vehicle enters a turn, the tires experience various forces, including lateral (sideways) forces due to the change in direction. Without traction understeer or oversteer may occur. Understeer occurs when the front tires lose traction during a turn, causing the vehicle to continue moving straight instead of following the desired path. It often results in a wider turning radius than intended. Oversteer happens when the rear tires lose traction during a turn, causing the rear of the vehicle to slide out. Oversteer can lead to a spin-out or a fishtailing motion.

4.5. Why Open Differential?

The differential used in Toyota Yaris is an open differential as is the case with most passenger cars. A question arises that if the clutch pack or torque biasing differential is the best among all, why aren't they used in the passenger cars? There are three main factors for choosing open differential over others [11]:

4.5.1. Cost and Affordability

Toyota targets the everyday car users who are willing to pay a reasonable price for their vehicles, rather than the high-end luxury market. A torque biasing differential enhances stability but at the cost of fuel efficiency. Therefore, for cost-effectiveness and affordability, an open differential is considered the optimal choice.

4.5.2. Traction Requirements

The target market for the Toyota Yaris expects minimal traction requirements, as it is designed for typical city and highway driving conditions. An open differential provides standard traction by distributing power equally between the wheels on an axle and is therefore suitable for normal on-road driving in cities.

4.6. Differential Gear Ratio:

Differential gear ratio often referred to as final drive ratio or axle ratio, ratio between rotational speed of vehicle's drive wheel and rotational speed of engine output shaft. It represents the number of revolutions the drive wheels make for each revolution of engine. For example, 3.73:1 means for each engine shaft rotation the drive wheel rotates 3.73 times. The greater the ratio the more the drive wheel rotates which required high torque multiplication. It is advantageous for low end acceleration and off-road performance. Lowering the ratio means less drive wheel rotations per engine rotation and hence will require less torque multiplication leading to fuel efficiency and less engine strain. The differential ratio used for our model is 4.055.

4.7. Maximum Steer Angle:

While the steer angle itself does not directly impact fuel efficiency, it is important to note that sudden or abrupt steering maneuvers, such as sharp turns or frequent lane changes, can contribute to increased rolling resistance, aerodynamic drag, and tire wear.

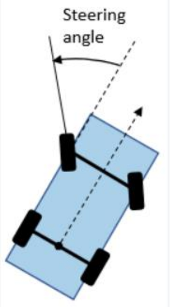


Figure 4.2: Steering Angle

Poor fuel economy might result from harsh braking, hard acceleration, and aggressive steering movements. Prioritizing adequate vehicle maintenance, such as routine tire pressure checks, and wheel adjustments is crucial for improving fuel efficiency.

The maximum steering angle for normal passenger cars typically falls within the range of 30° to 38°. In the case of our car, the maximum steering angle is specifically set at 32°.

4.8. Toe Angle:

Toe angle is the angle between the longitudinal axis of vehicle and direction in which wheels are pointed. It is typically measured in degrees and can be positive or negative.

Positive toe angle: The wheels are angled inward towards the centerline of the vehicle.

Negative toe angle: The wheels are angled outward away from the centerline of the vehicle.

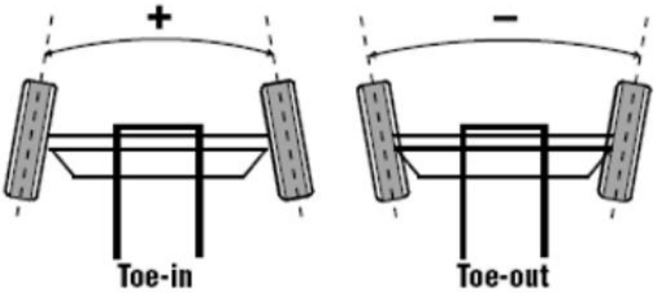


Figure 4.3: Toe Angle

Proper alignment is necessary or else it influences rolling resistance. Typically, it ranges from 0.1° to 0.5°. The toe angle is set at 0.1° for our model.

4.9. Ackermann Steering:

Named after German Engineer Rudolph Ackermann, Ackermann steering ensures all four wheels follow different turning radii when the vehicle is turning. Inside wheels follow tighter turning radius (pivots more sharply) than outside wheel. Vehicle has better stability and avoids slipping. It reduces tire drag. In the simple four bar steering mechanism the tires turn at the same slip angles whereas in Ackermann steering mechanism the inner and outer tires turn at different slip angles. Another alternative is Davis steering mechanism.

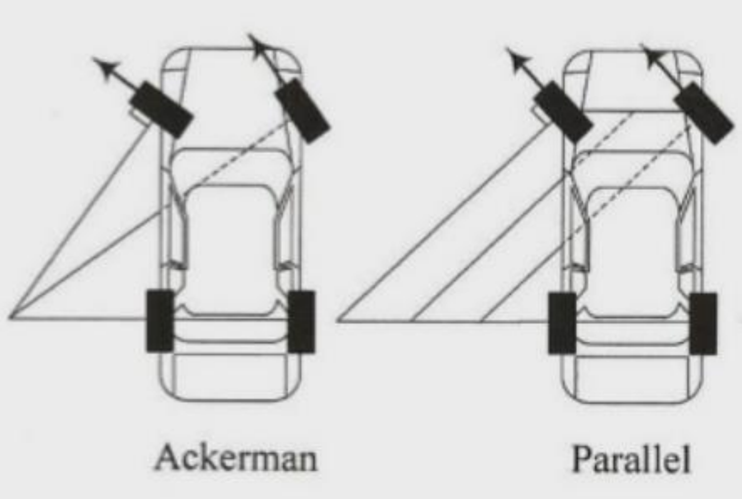


Figure 4.4: Ackerman vs Parallel

Chapter 5: Vehicle Physics II

5.1. Maximum Brake Torque:

Maximum Brake Torque is the maximum amount of torque or rotational force that can be generated by the braking system to slow down vehicles. It represents the highest level of braking performance that can be achieved [12]. Brake torque is given as:

$$T_b = F_b r_e \qquad (1)$$

Where r_e is the effective radius.

Effective radius is defined as the distance between center of wheel and point of contact between brake pad and rotor (disc).

The value of maximum brake torque ranges from 100 to 400 Nm for passenger cars, 400 to 800 Nm for sports cars and 800 to 3000 Nm for heavy duty vehicles. For our car it is taken to be 150 Nm.

5.2. Brake Bias:

Brake bias is defined as proportion of brake force applied to front and rear wheels. For most front wheel drive cars, the brake bias is 80% which suggests that approximately 80% of the braking force is being applied to the front wheels, while the remaining 20% is being applied to the rear wheels. In case of rear wheel drive the value is between 60-70%. For our model it is taken as 80%.

5.3. Torque Distribution and Front-to-Rear Ratio:

The brake bias is 80%:

Front: - $150 \times 80\% = 120\ Nm$ Rear: - $150 \times 20\% = 30\ Nm$

For neutral, it is equal to one half of the max brake torque which is equal to $\frac{150}{2} = 75$.

Front to Rear ratio is equal to $\frac{120}{30} = 4$.

5.4. Handbrake Torque and Axle:

The amount of rotational force or torque that can be generated by handbrake or parking brake system of a vehicle. The value ranges from 100 to 250 Nm for passenger cars. For our car, the value is set as 120 Nm. The primary braking system is designed for normal braking during driving, using hydraulic pressure or electronic signals to activate brake pads. It provides higher braking force than handbrake. Handbrake prevents the vehicle from rolling or moving, it has a separate brake mechanism. The handbrake axle is the rear axle.

5.5. Combined Retarder Brake:

A combined retarder braking system is commonly used in heavy duty vehicles to provide additional braking power and assist in vehicle declaration. It combines the features of a hydraulic retarder (that uses resistance of a high viscosity fluid to generate braking force) and engine brake into a single integrated system. It is not a present feature in our car, so it is disabled.

5.6. Tires Friction:

Five tire friction models were studied, here is an overview of all:

5.6.1. Flat Friction Model

The flat friction model is the simplest form of tire friction model. It does not consider any parameters or factors that influence tire behavior. In this model, the tire forces are directly proportional to the normal load acting on the tire.

$$F = \mu N \qquad (2)$$

Where μ is the constant friction coefficient and N is the normal load on tire.

5.6.2. Linear Friction Model

The linear friction model is an improvement over the flat friction model and included slip ratio (the difference between the actual wheel speed and the ideal wheel speed). This model also assumes a constant friction coefficient.

$$F = \mu N S \qquad (3)$$

Where S is the slip ratio

5.6.3. Parametric Friction Model

The parametric friction model considers additional parameters that affect tire behavior, such as the longitudinal slip, camber angle, and vertical load. It involves a more complex set of equations with multiple parameters that can be fitted to experimental data.

$$F = F_y(F_z, \alpha, \kappa, \gamma) \qquad (4)$$

Where:

- F is the tire force,
- Fz is the vertical load on the tire,
- α is the camber angle which is defined as the angle between the wheel and the car's body,

- κ is the slip ratio or slip angle,
- γ is another parameter that may represent additional effects.

5.6.4. Smooth Friction Model

The smooth friction model is an extension of the parametric friction model. It includes additional factors such as tire compliance, nonlinearities, and dynamic effects.

$$F = F_y(F_z, \alpha, \kappa, \gamma, \omega) \qquad (5)$$

Where:

- F is the tire force,
- Fz is the vertical load on the tire,
- α is the camber angle which is defined as the angle between the wheel and the car's body,
- κ is the slip ratio or slip angle,
- γ is another parameter that may represent additional effects,
- ω is the tire angular velocity

5.6.5. Pacejka Friction Model:

The Pacejka friction model, or the Magic Formula, is a more advanced and widely used tire model that captures the complex behavior of tires. It incorporates nonlinear terms and considers various influencing factors such as slip ratio, slip angle, camber angle, and vertical load. The Magic Formula consists of multiple equations with coefficients that are fitted to experimental data [13].

$$F_y = D * sin(C * atan(B * \alpha - E * (B * \alpha - atan(B * \alpha)))) \qquad (6)$$

- F_y is the lateral force (sideways force) generated by the tire.
- α is the slip angle, which is the angle between the tire's heading direction and the direction of travel.
- $B, C, D,$ and E are the empirical coefficients that depend on the tire and its characteristics. These coefficients are determined through experimental testing and parameter fitting.

The model used for our car is Pacejka Friction Model. The accurate values of the empirical coefficients for Toyota Yaris were not found therefore the values were assumed using literature.


Friction Model: Pacejka

A Adherent μ: 0.95

B Stiffness: 0.8

C Shape: 1.5

D Peak μ: 1.1

E Curvature: -2

Figure 5.1: Empirical Coefficients of Magic Formula

- Adherent: friction when the tire does not slip.
- Peak: maximum friction of the tire, typically produced when it experiences a small amount of slip.
- Limit: if the slip increases beyond the peak point the friction is progressively reduced until reaching a minimum value

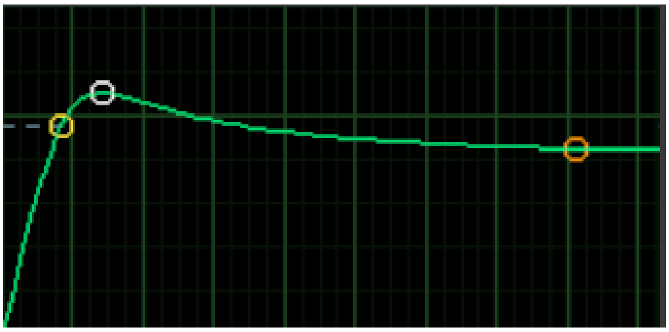


Figure 5.2: The yellow, white, and orange circles on the horizontal slip (m/s) versus coefficient of friction (μ)

5.7. Engine:

The engine is the beating heart of a vehicle, delivering the force and performance required to move the vehicle ahead. Several engine parameters must be studied that are included in the Unity 3D game.

Idle RPM refers to the rotational speed of an engine when it is at rest or stationary position. It is the lowest RPM at which the engine can sustain a stable and smooth operation without acceleration or load. Idle Torque refers to the amount of rotational power that an engine produces at idle RPM. Idle torque is important for ensuring the engine can provide ample power for vital functions such as powering the alternator, air conditioning, and other accessories while the vehicle is stationary. Peak RPM refers to the specific rotational speed at which an engine generates its maximum power output. It is the point on the engine's RPM range where it achieves the highest level of performance and efficiency. Peak Torque represents the maximum rotational power that an engine can generate. The combination of peak RPM and peak torque is critical for recognizing the engine's power characteristics as it indicates the RPM range at which the engine operates most efficiently [14].

Active and passive idle controls are two different methods to managing the idle speed of an engine when the vehicle is stationary:

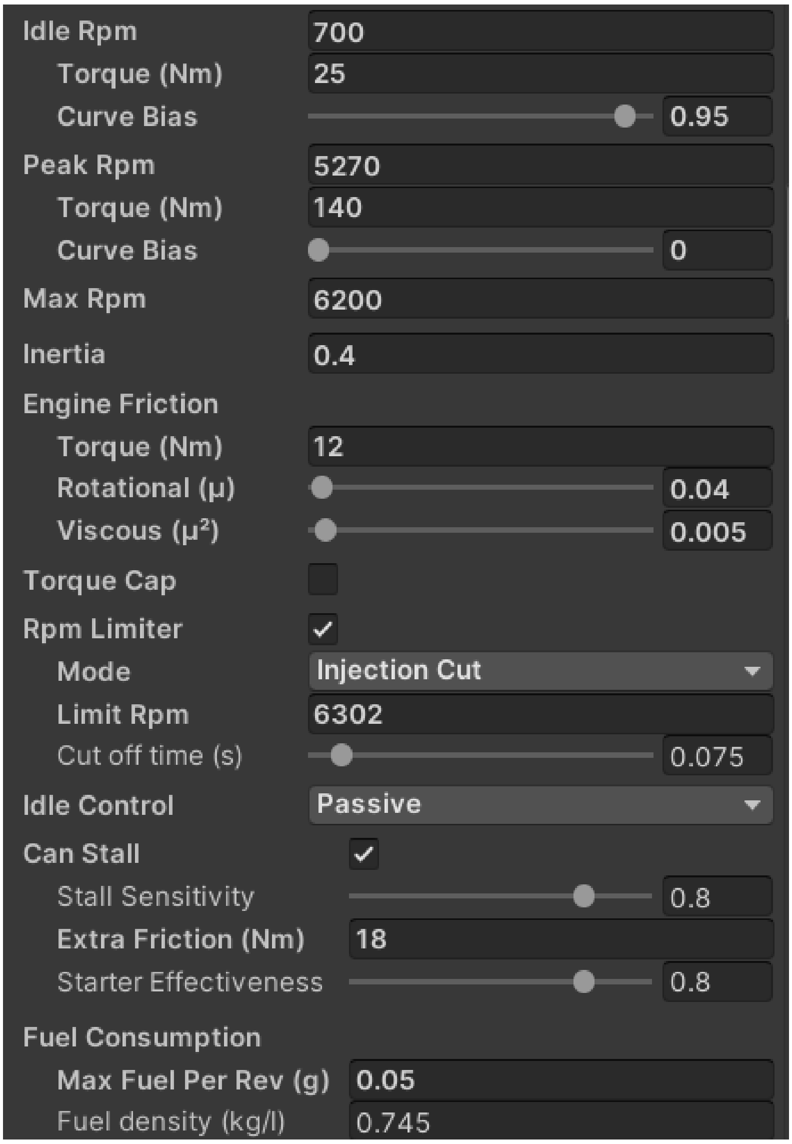
1) Active Idle Control: Utilizing a specialized system or electronic control module, active idle control actively controls and modifies the engine's idle speed. This control system keeps track of several variables, including temperature, engine load, and driving conditions. To maintain a constant and ideal idle speed, it might modify the throttle position, fuel injection, or ignition timing according to these inputs. Modern vehicles with computerized engine management systems frequently have active idle control systems.

2) Passive Idle Control: The mechanical systems and components used in passive idle control, sometimes referred to as conventional idle control, are what keep the idle speed constant. The idle speed is not actively adjusted or regulated in response to real-time inputs. Instead, during vehicle assembly or through manual changes, a mechanical idle speed control device, such as an idle air control valve (IACV), is employed to set the idle speed. Once established, the passive idle control system keeps the idle speed constant without actively reacting to shifting circumstances.

Rotational engine friction refers to the frictional forces that limit the free motion of rotating engine components, for example the crankshaft, pistons, connecting rods, and bearings. It depicts the energy losses generated by these frictional forces inside the engine. Since the lubricating oil is viscous, there is a certain form of friction called viscous engine friction that occurs inside the engine. It describes the barrier to motion that engine parts encounter when they pass through the oil coating.

Fuel density is equivalent to the mass of fuel per unit volume. Usually, it is expressed as a ratio of grammes per milliliter (g/mL) or kilograms per liter (kg/L). Different forms of fuel can have varying densities. Here are some rough estimates for the densities of some common fuels:

- Diesel: 0.82 - 0.86 kg/L
- Gasoline: 0.72 - 0.78 kg/L
- Ethanol: 0.78 - 0.79 kg/L
- Natural Gasoline: 0.68 - 0.74 kg/L



Idle Rpm	700
Torque (Nm)	25
Curve Bias	0.95
Peak Rpm	5270
Torque (Nm)	140
Curve Bias	0
Max Rpm	6200
Inertia	0.4
Engine Friction	
Torque (Nm)	12
Rotational (μ)	0.04
Viscous (μ²)	0.005
Torque Cap	☐
Rpm Limiter	☑
Mode	Injection Cut
Limit Rpm	6302
Cut off time (s)	0.075
Idle Control	Passive
Can Stall	☑
Stall Sensitivity	0.8
Extra Friction (Nm)	18
Starter Effectiveness	0.8
Fuel Consumption	
Max Fuel Per Rev (g)	0.05
Fuel density (kg/l)	0.745

Figure 5.3: Engine Parameters

The Curve Bias parameters have some influence in the transitions between Idle and Peak. The inertia defines how much effort takes to modify the rpm in the engine. Formula 1 style engines have very little inertia (0.1-0.2), while trucks have a large inertia in their engines (8-10). Standard cars are around 0.3 and 1.

Rpm Limiter limits the rpm the engine can reach.

If the engine Can Stall the parameters can be configured as well:

Stall Bias: how "easy" is to stall the engine once the rpm falls below the idle value. 0 means the engine is hard to stall. 1 means easy to stall.

Extra Friction (Nm): a stalled engine increments the engine friction by this value.

Starter Reliability: how easy is to the starter to start the engine. 0 will not likely be able to start the engine. 1 will quickly start the engine. Intermediate values (depending on the actual engine settings) gradually add some difficulty and random factor.

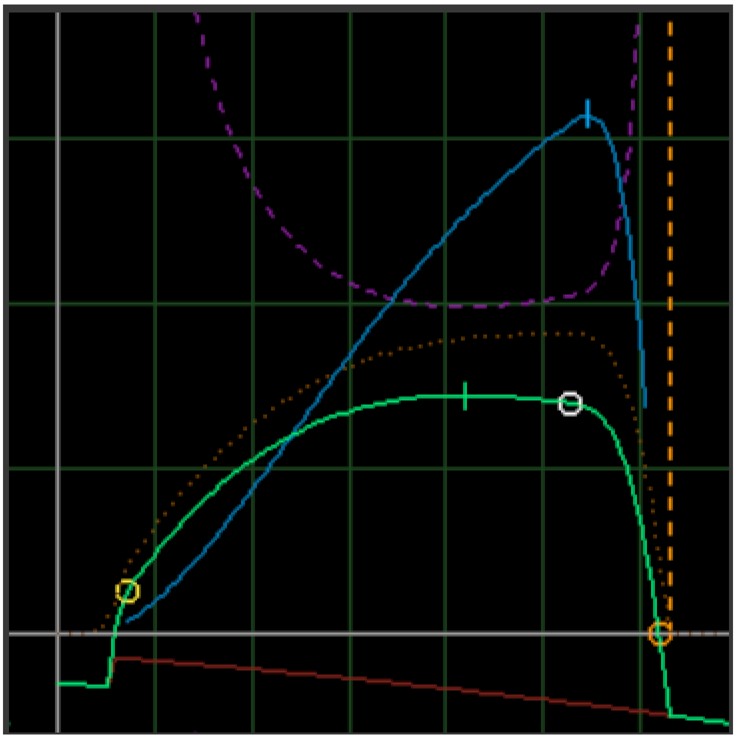


Figure 5.4: Engine Curves

The legend for the graph is:

Horizontal Scale: rpm × 1000

Vertical Scale: torque × 100

Green: Engine torque curve

Dotted orange: Combustion Engine Torque

Blue: Engine power curve

Dashed Orange: Rev Limiter

Red: Engine Friction

Dotted Purple: Specific fuel consumption

The engine torque curve is the sum of two curves: ideal torque curve (dotted orange) and friction torque curve (red). The result of adding those curves together is the final engine torque curve (green).

The final torque curve (green) is guaranteed to cross three key values:

- Idle (yellow circle): rpm and torque (Nm) at idle.
- Peak (white circle): rpm and torque (Nm) where the ideal engine produces the maximum torque. This is not necessarily the same point where the maximum final torque is reached.
- Max (orange circle): rpm where the resulting torque becomes zero.

The Engine Friction (red curve) produces the engine brake effect when no throttle is applied. It is defined by a base Torque (Nm) and two coefficients of friction, Rotational ($\boldsymbol{\mu}$) and Viscous ($\boldsymbol{\mu^2}$). The effect of these parameters can be lively observed in the graph.

Torque Cap clamps the torque curve (green) with the given value. This simulates an electronically imposed torque limit.

The Idle Control configures the extra torque required to keep the engine running. Also provides smooth throttle values near the idle rpm (dotted white curve).

5.8. Clutch:

5.8.1. Lock ratio clutch:

A lock ratio clutch is a part of an automatic gearbox system that mechanically connects the torque converter on the engine to the input shaft of the gearbox. This prevents slip and establishes a direct mechanical connection between the engine and the gearbox [15].

5.8.2. Friction disc clutch:

A friction disc clutch is a type of clutch mechanism that engages and disengages power transmission between the engine and the transmission using friction plates (discs).

5.8.3. Torque Converter Clutch

The torque converter clutch, a component of automatic gearboxes, secures the turbine and impeller of the torque converter together, preventing slide and establishing a mechanical connection.

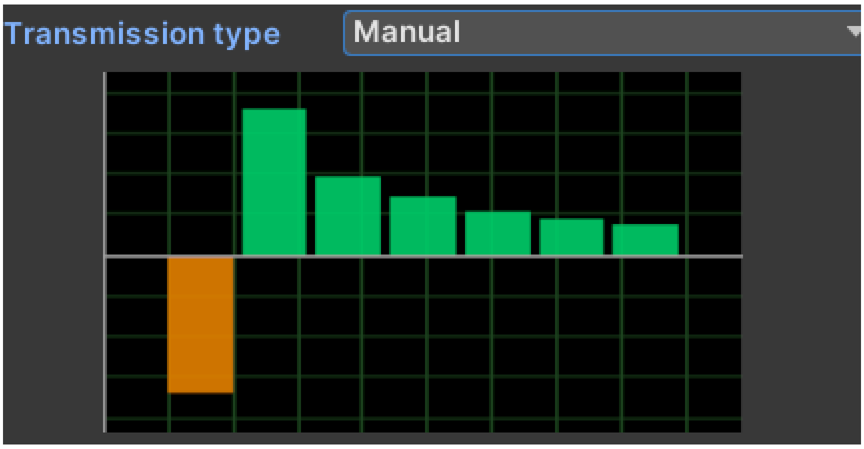
5.8.4. Torque converter limited clutch:

Under some circumstances, the torque converter's internal system places a limit on the amount of torque that may be delivered.

When the torque converter is locked, the output speed to input speed ratio is referred to as the lock ratio bias. For our car torque converter limited has been used.

5.9. Gearbox:

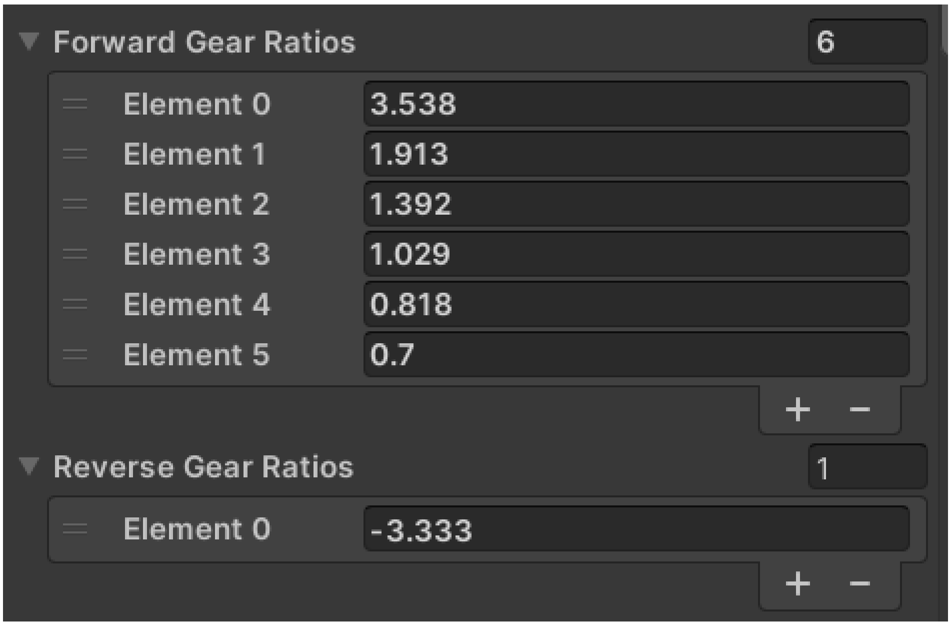
The transmission type is set to manual as with the case of Toyota Yaris 6-speed M/T.



Transmission type: Manual

Figure 5.5: Gearbox graph of Toyota Yaris

A gear ratio is the number of revolutions made by a driving gear as compared to the number of revolutions made by a driven gear of a different size. The gear ratios were chosen from the Toyota Yaris 1.5L manual.



Forward Gear Ratios	6
Element 0	3.538
Element 1	1.913
Element 2	1.392
Element 3	1.029
Element 4	0.818
Element 5	0.7

Reverse Gear Ratios	1
Element 0	-3.333

Figure 5.6: Gear ratio values used

5.10. Suspension:

Suspension distance is range that represents the vertical distance that the suspension system allows the wheels to move up and down to absorb bumps and maintain contact with the road surface. This range represents the vertical distance that the suspension system allows the wheels to move up and down to absorb bumps and maintain contact with the road surface [16].

Springs sustain the weight of the vehicle. A good starting point is configuring the spring rate (N/m) so each suspension can support up to twice of the distributed weight. Thus, if the weight is evenly distributed then each suspension would be at half of its travel at rest.

The rule of thumb for the spring rate is:

Spring Rate = vehicle mass / number of wheels * 2 * 9.81 / suspension distance (7)

Dampers (or shock absorbers) limit the suspension movement and damp the spring oscillations. The damper setup affects the angular momentum of the vehicle on weight shifting situations (accelerating, braking, cornering).

The damper rate (N/ms-1) should be configured so the oscillating behavior resembles the real vehicle.

The rule of thumb is for the damper rate is:

Damper Rate = Spring Rate / 20 (8)

5.11. Driving Assists:

5.11.1. Anti-Lock Braking System (ABS):

Vehicles with ABS (Anti-lock Braking Systems) have a safety feature that keeps the wheels from locking up while braking, allowing the driver to keep control of the steering. It adjusts brake pressure to each tire separately, lowering the risk of skidding and enhancing stopping effectiveness.

5.11.2. Traction Control System (TCS):

Wheel slippage during acceleration is a problem that the TCS (Traction Control System) feature helps to avoid. To regain traction and stop wheel spin, it recognizes when one of the driven wheels is spinning more quickly than the other wheels and applies brake pressure or lowers engine power.

5.11.3. Stability Control System (ESC):

A system called ESC (Electronic Stability Control) was created to increase a vehicle's stability and control under different driving circumstances. It compares the intended direction of the vehicle with the actual direction using sensors to determine which is correct. To help the vehicle return to its intended trajectory if it deviates off track, the ESC can selectively apply individual brakes and modify engine power.

5.11.4. Anti-Spin Regulation (ASR):

ASR assists in preventing wheel spin during acceleration in low-traction circumstances. ASR works by reducing engine power and delivering brake pressure to the sliding wheels to maintain enhanced traction and stability. It aims to improve overall driving safety and control.

Chapter 6: Key Concepts Related to Longitudinal Performance

6.1. Slip Angle:

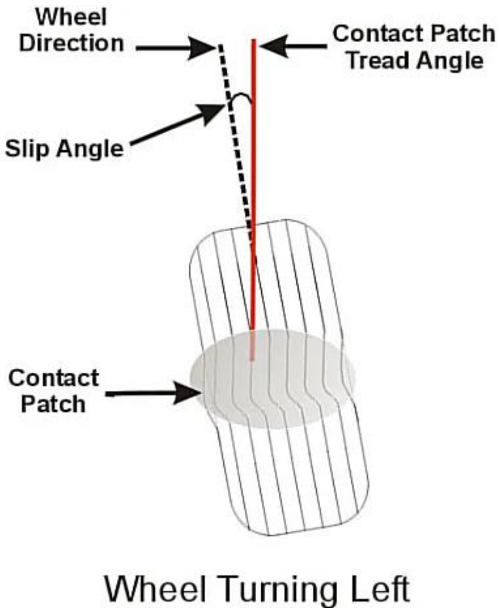


*Figure 6.1:*Slip Angle

Slip angle is the angle between the direction the wheel is pointing and the direction in which it is moving. When the vehicle makes a turn, some lateral forces act on the tire which result in deviation in direction the wheel is pointing and the direction at which it is moving.

The contact patch refers to the portion of a tire that is in direct contact with the road surface at any given time. When a tire is properly inflated and carrying the weight of a vehicle, it deforms slightly, creating a flattened area on the tread that makes contact with the road.

For normal driving and cornering, slip angles typically range from 1 to 5 degrees. This indicates a slight deviation of the tire from the direction it is pointing. During aggressive driving, slip angles can increase up to 5 to 10 degrees.

When a vehicle enters a turn, the tires experience various forces, including lateral (sideways) forces due to the change in direction. Without traction understeer or oversteer may occur. Understeer occurs when the front tires lose traction during a turn, causing the vehicle to continue moving straight instead of following the desired path. It often results in a wider turning radius than intended. Oversteer happens when the rear tires lose traction during a turn, causing the rear of the vehicle to slide out. Oversteer can lead to a spin-out or a fishtailing motion [17].

6.2. Slip Ratio

Slip ratio is the ratio between the difference in actual speed and the rotational speed of a tire.

$S = (V - Vr) / Vr$ (9)

Where:

V is the actual speed of the tire (vehicle speed)

V_r is the rotational speed of the tire (given by the formula $Vr = 2\pi rN$, where r is the tire radius and N is the tire's rotational speed in revolutions per unit time)

By monitoring and controlling slip ratio, vehicle systems such as anti-lock braking systems (ABS) and traction control systems (TCS) can adjust braking and power distribution to optimize grip and stability.

Slip ratios during normal driving conditions are typically close to zero or slightly positive. This means the tire is rotating at nearly the same speed as the vehicle. During braking, slip ratios can range from 0 to 0.3 or higher, indicating a relative slip between the tire and the road surface.

During acceleration, slip ratios can range from 0 to -0.3 or lower, indicating a relative slip in the opposite direction, with the tire rotating faster than the vehicle's speed.

6.3. Rolling Friction:

In the constant rolling friction model, the rolling friction force remains constant regardless of the influencing factors. In the linear rolling friction model, the rolling friction force is directly proportional to the load or weight on the tire. In the quadratic rolling friction model, the rolling friction force is proportional to the square of the load or weight on the tire. For simplicity constant dynamic model is used for rolling friction. The three parameters required for the rolling friction model are dynamic coefficient, rolling coefficient and static speed threshold. The dynamic and rolling coefficients represent the ratio of rolling friction force to the normal force between the tire and road surface when tire is in motion and when it is at rest, respectively. The static speed threshold refers to the minimum speed at which the tire transitions from static friction to dynamic friction. Below this speed, the tire experiences static rolling friction, and above this speed, it experiences dynamic rolling friction [18].

6.4. Aerodynamic Drag:

The longitudinal position is the location along the length of the vehicle where the drag force is acting, it is set around the middle of the front rear axles. Typically, it is measured from the front bumper or center of gravity.

Aerodynamic drag is directly proportional to the square of the speed of the vehicle.

$$Drag\,force = 0.5 * Cd * A * \rho * V\text{^}2 \qquad (10)$$

Where:

- Drag force is the force of aerodynamic drag acting on the vehicle.
- C_D is the coefficient of drag
- A is the frontal area of the vehicle.
- ρ is the density of the air.
- V is the velocity of the vehicle.

6.4.1. Drag coefficient (Cd): -

This value has the most influence in the top speed of the vehicle. A good value for standard cars is around 0.2-0.35. It represents the vehicle's aerodynamic efficiency. To reduce the value of drag coefficient the following key areas are to be considered:

1) **Maintain attached flow**: - Use a streamlined shape.

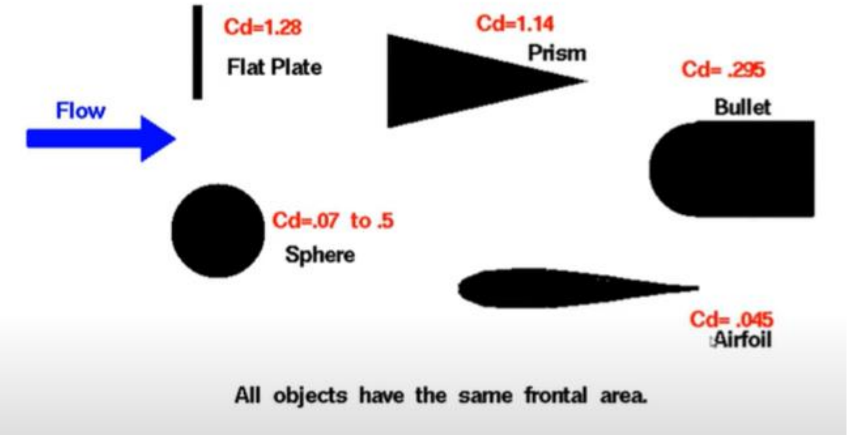


Figure 6.2: Drag coefficients for different frontal areas

2) **Maximize Laminar Boundary Layer**: Have gentle curves on forebody and use an excellent surface finish.

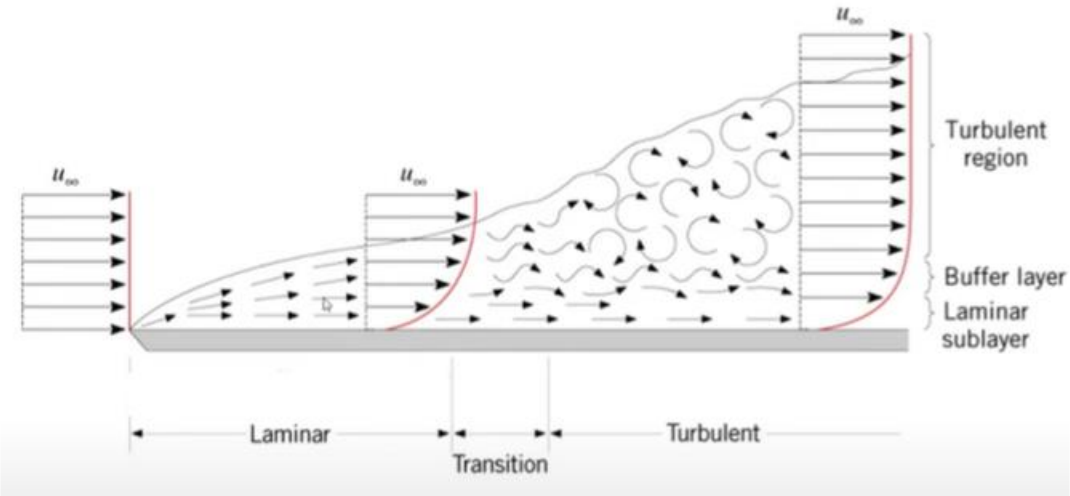


Figure 6.3: Advantage of gentle curves on laminar boundary

3) **Have Zero Lift: -** The underside of the vehicle needs to be shaped to give a low lift. Lift causes an induced drag.

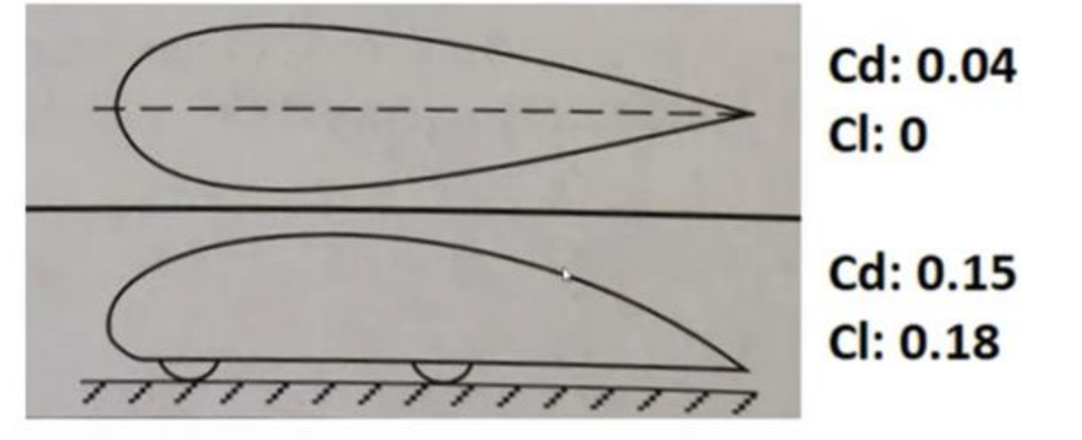


Figure 6.4: Reducing lift below the vehicle

4) **Minimize Frontal Areas: -** When viewed from the front, make the vehicle area as small as possible.
5) **Minimize Interference Drag: -** Blend all surfaces with smooth curves such that there are less/no corners. Ensure a smooth surface finish on the vehicle's body to minimize surface roughness and turbulence. Avoid unnecessary protrusions, gaps, or rough textures that can disrupt the airflow.

Besides these factors, the aerodynamic spoilers, side mirrors and windshield wipers and wheel design also contribute to reduction in coefficient of drag. The coefficient of drag for the vehicle is set at 0.31. Handling at low-mid speeds is mainly affected by suspension and inertia. Handling at high speeds is mainly affected by aerodynamics [19].

Chapter 7: Acquisition and Analysis of Data

The real-time data is retrieved from unity data bus and exported to MATLAB directly to help in analyzing the effect of different parameters on fuel consumption. The parameters include vehicle speed, engine rpm, engine load, engine power, engine torque, throttle, and brake positions. The following graphs are obtained from a test drive in Unity 3D.

7.1. <u>Test Drive#1</u>

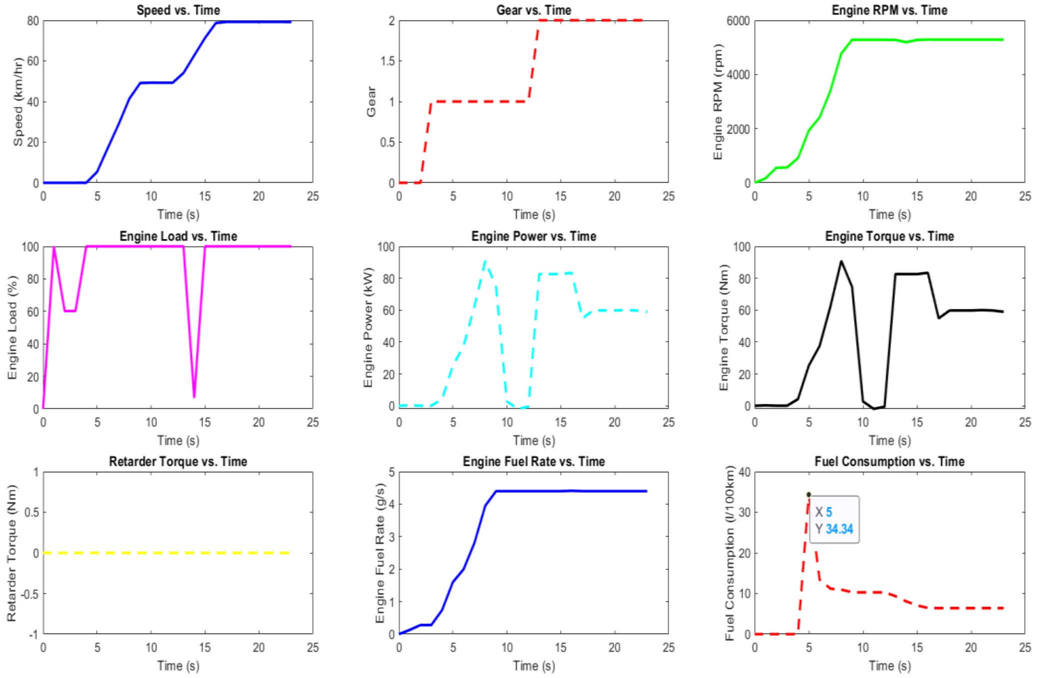

Speed vs. Time
Gear vs. Time
Engine RPM vs. Time
Engine Load vs. Time
Engine Power vs. Time
Engine Torque vs. Time
Retarder Torque vs. Time
Engine Fuel Rate vs. Time
Fuel Consumption vs. Time

Figure 7.1 A: Test drive#1

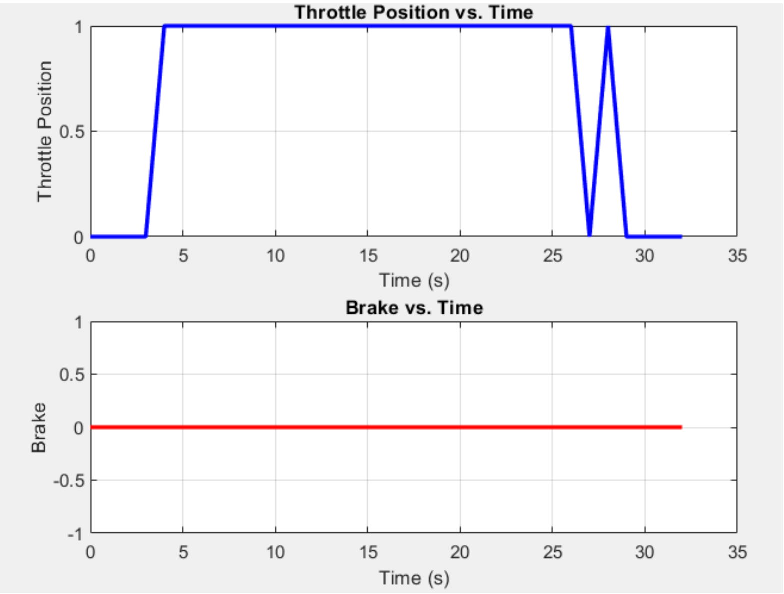


Figure 7.1 B: Test drive#1

Let us take some test points for analyzing the data:

Table 7.1: Input points for test drive#1

Maximum instant fuel consumption occurs	at t= 5 seconds.
Vehicle Speed	5.36 km/hr
Gear	1
Engine Speed	1927.23 rpm
Engine Load	100
Engine Powe	25.17 kW
Throttle Position	100%
Brake Pedal Position	0%

7.2. **Test Drive#2**

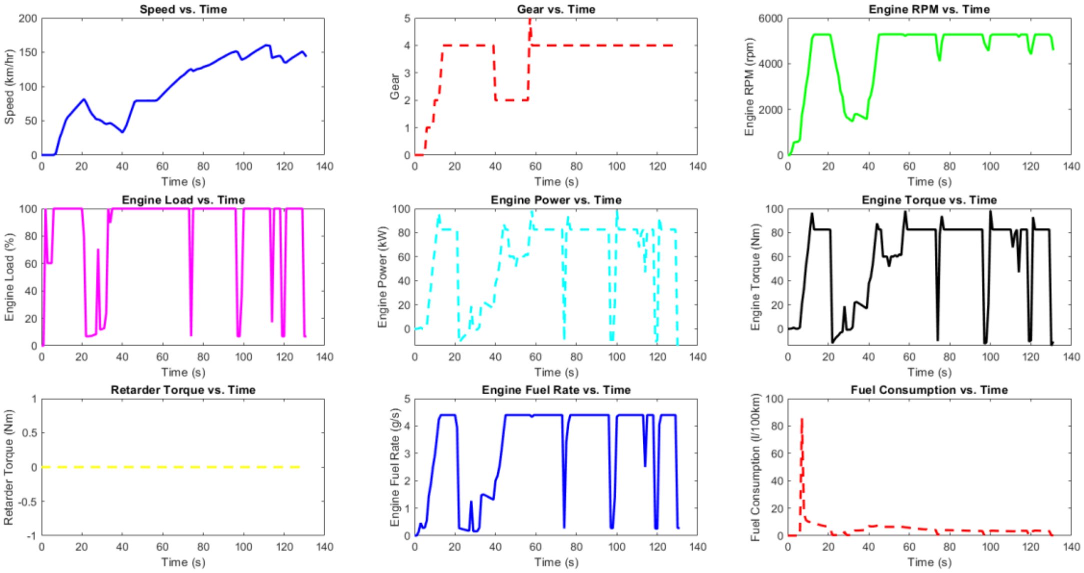


Figure 7.2 A: Test drive#2

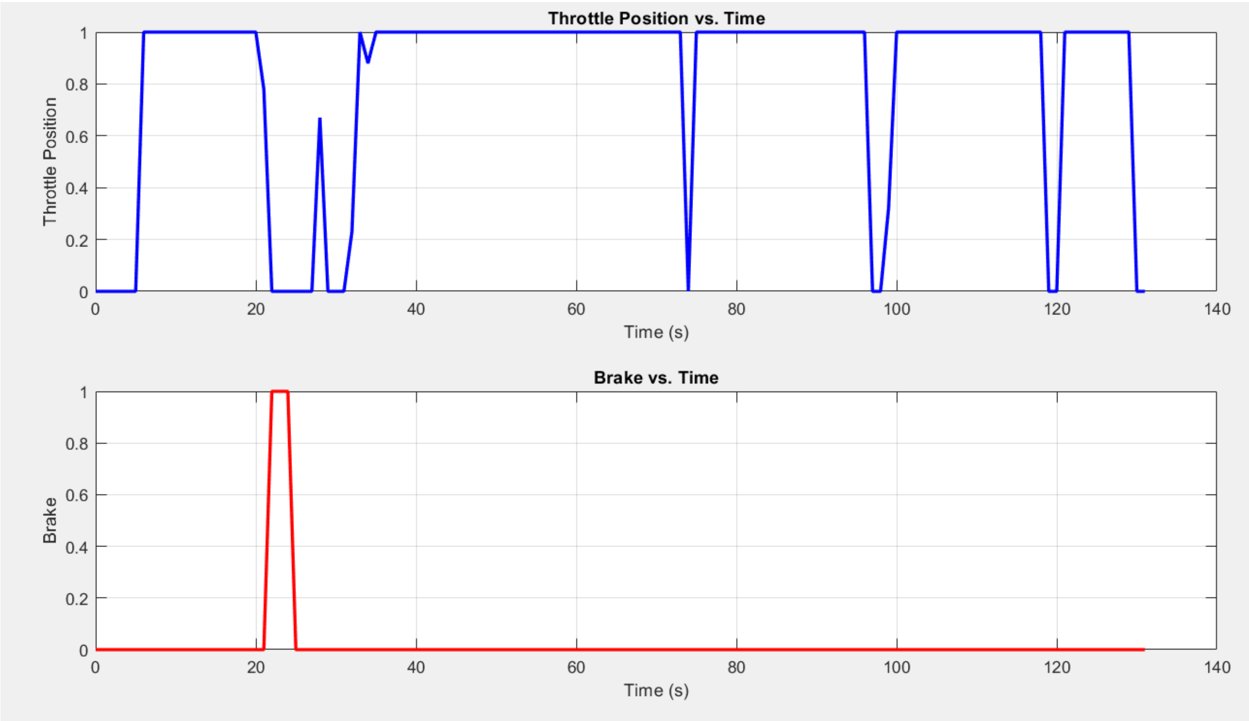


Figure 7.2 B: Test Drive#2

Let us take some test points for analyzing the data:

Table 7.2: Input points for test drive#2

Maximum engine fuel rate	occurs at t= 60 seconds.
Vehicle Speed	88.59 km/hr
Gear	4
Engine Speed	5275.53 rpm
Engine Load	100%
Engine Power	82.61 kW
Throttle Position	100%
Brake Pedal Position	0%

Similarly analyzing the test drive cycles multiple times result in the following conclusions:

1) The engine rpm in the range of 2000-3000 rpm is best for fuel efficiency.

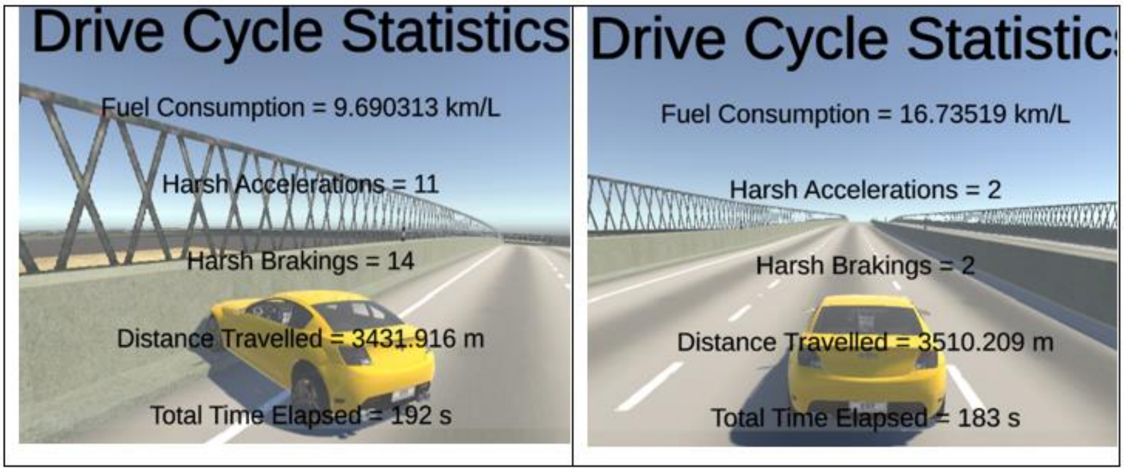
2) The vehicle speed with appropriate gear applied results in best fuel efficiency:

Table 7.3: Speed ranges for different gears

0-10 km/hr	1st Gear
10-25 km/hr	2nd Gear
25-45 km/hr	3rd Gear
45-65 km/hr	4th Gear
65-85 km/hr	5th Gear
85+ km/hr	6th Gear

3) A greater engine load along with low rpm results in better fuel efficiency.
4) The engine power shall be in range of 35-50 kWh (for passenger cars)
5) The closer the throttle position is to 50% higher is the fuel efficiency but obviously this cannot be the case in real driving cycle, so the range of 40-70% throttle position is considered moderate.
6) Harsh Brakes should be avoided. Brake pedal position from 0 to 50% in a linear way while applying brakes is ideal.

Based on these conclusions the unity code was developed to give the driver real time feedback to teach him fuel efficient driving behavior. A comparison of a driver's driving statistics with the feedback mode on and off is shown.



Drive Cycle Statistics

Fuel Consumption = 9.690313 km/L

Harsh Accelerations = 11

Harsh Brakings = 14

Distance Travelled = 3431.916 m

Total Time Elapsed = 192 s

Drive Cycle Statistic

Fuel Consumption = 16.73519 km/L

Harsh Accelerations = 2

Harsh Brakings = 2

Distance Travelled = 3510.209 m

Total Time Elapsed = 183 s

Figure 7.3: Comparison of Fuel Consumption

A difference of almost 44% can be seen for the case when the feedback is followed accordingly. The above comparison can be considered as the worst vs best case but the spirit behind the comparison is to encourage use of feedback-based mode for teaching driver fuel efficient techniques.

Chapter 8: Interfacing with Logitech

8.1. Study and Selection of Logitech

The Logitech components are a type of racing peripherals designed to be used in driving simulation. Our driving force consists of three parts

8.2. Steering Wheel

- Degree of rotation: 900 deg
- Sensor for hall effect

Figure 8.1: Logitech G27

- Vibration feedback
- Overheating of device safety

8.3. Gearbox

- Six speed
- Push-down reverse gear shifter

8.4. Pedals

- Non-linear pedals for braking
- Customized grip
- Customized heel type grip
- Auto-calibration

This includes real-time adjustment controls for control settings in braking and traction while driving. Users can choose the gears via buttons at the back side of the steering, or change gears using a dashboard at the right of the wheel. The vibration feedback comes from graphics of the physical engine of the game and simulations of “road feel".

8.5. Study and Selection of Graphics/Game

Live for Speed (LFS) is a single player/multiplayer racing simulator and is easy to connect with Logitech racing force components. It provides real life driving training for the multiplayers and single player drives in competition with AI traffic. One of the main reasons to choose this game was it is easy to interface settings with Simtools and our controller.

8.6. Controls

Game controls are configured here. Initially, the mouse control config controls are configured. Select "Wheel / Joystick" to assign functions to our wheel buttons and axles. select Axes / FF then click on Steer. As we turn our wheel, one of the rods on the left should move. Select the next button to assign direction to the correct axis. Repeat this process for accelerator and brake. If they go in the wrong direction, select the invert to correct it.

Figure 8.2: LGS Software

8.7. Steering Controls Manual:

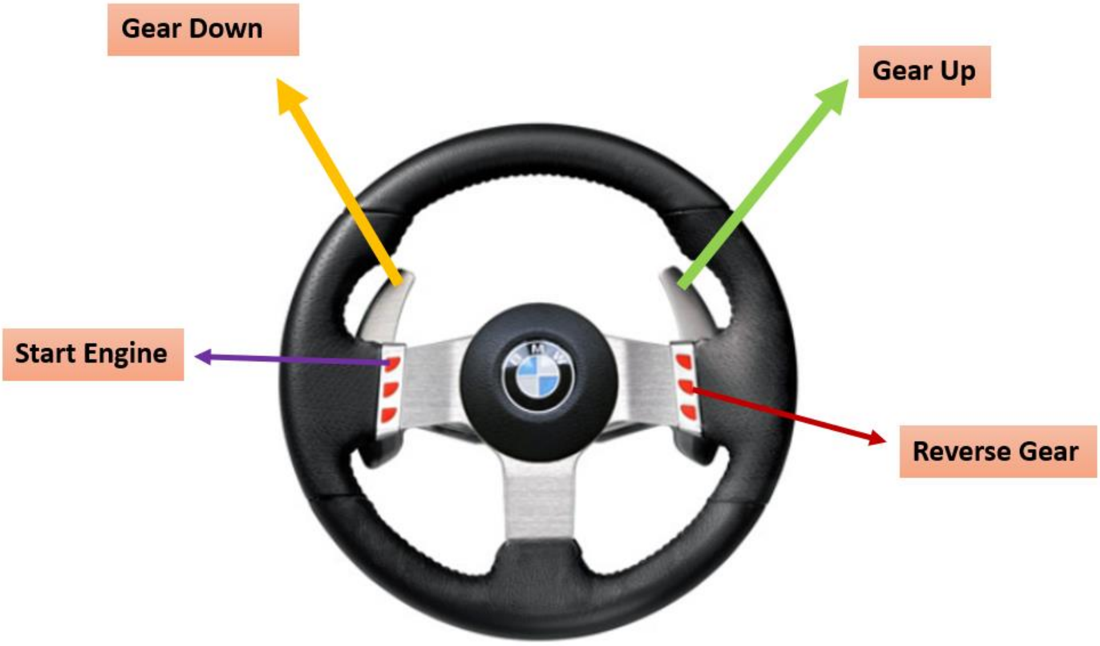


Figure 8.3: Steering Manual

8.8. Connections of Logitech

Wire from our Logitech steering wheel connects via USB to the our windows PC

- Connect USB dongle to USB ports on the PC
- Connect wires from gearbox and pedals to USB ports available on backside of steeringwheel
- Connect power cable to the Logitech
- Switch the power on
- Logitech will calibrate automatically after connecting USB to PC

8.9. Logitech G-Hub

To use Windows PCs, we require a software for controlling sensitivities of Logitech components. It will automatically connect devices. Explained settings of each component are provided below.

8.10. Steering Wheel

8.10.1. Sensitivity

Default is 50. Alters the output response of the wheel to be more or less sensitive.Sensitivity increases within range of 51% and 100% and decrease between 0% and 49% Operating Range

Default is 900 (450° either side), which is the maximum range. For example, setting the operating range to 180 would have 90° either side.

8.11. Centering Spring in Force Feedback Games

Unticked by default. For most titles, we would normally have this disabled off because the games will be modelling the correct return to center function of our wheelbased on what the virtual car is currently doing.

8.12. Centering Spring Strength

Default is 10. Adjust the value of this to our preference. 100 being the strongest spring strength, 0 being no centering spring at all.

8.13. Per-Profile Steering Wheel Settings Lock

Per-profile steering wheel settings lock in Logitech refers to the feature that allows users to save and lock specific steering wheel settings for different profiles or games. Logitech steering wheels, such as the one we are using, come with software that enables users to customize and fine-tune various aspects of the wheel's performance, including pedal sensitivity, force feedback, and button assignments. Lock this to set the Steering Wheel configuration for all our profiles.

8.14. Pedal Sensitivity

Here we can configure our pedals sensitivity and combine the Gas and Brake into a single axis for certain games that only support a single axis for acceleration. Covers the 3 axis and the sliders have the same behavior as the Steering Wheel sensitivity. The slider alters the output response of the axis to be more or less sensitive. Leaving this slider at 50% will provide a linear 1:1 output. Between 51% and 100% will make the axis increasingly more sensitive. Between 0% and 49% will make the axis decreasingly sensitive. Sentsitivies can be set as:

- **Clutch**: Default is 50, range 0-100.
- **Brake**: Default is 50, range 0-100.
- **Accelerator**: Default is 50, range 0-100.
- **Combined Pedals**: If checked, this will set the Accelerator and Brake pedals to become two halves of a singleaxis. This will help the pedals operate correctly in older racing titles that do not support separate axes for pedals.

Chapter 9: Fabrication & Analysis

A complete simulator consists of a software to run the simulation and a hardware rig to help the driver interact with the program in a realistic manner. This phase focuses on fabricating a physical structure in which a driver can sit and interact with certain controls as he would in a real car. These controls include steering wheel, pedals, gear shifter, monitor, etc. Mimicking the inside of an actual car in our rig will help the driver compare the simulation experience to the road experience. The simulation program coded with the research data is run on the rig system and together they make a complete simulator demonstrating the longitudinal performance of a vehicle.

The driver can sit down in the seat and use the controls attached in the rig to drive the virtual car. His actions are noted in the system and evaluated at the end in terms of fuel consumption and car handling. The custom hardware affixed in the rig is unlike conventional computer controls. To enable this hardware to give input to the program, special Logitech hardware is used. The device senses the movement on every component and feeds the data to the simulation program. This would give the sense of driving the car. The attributes of the car’s interior that depend on the driver and can adversely affect fuel consumption will be provided in the physical structure [20].

SolidWorks is software used for solid modeling of computer-based design and engineering computer program that runs primarily on Microsoft Windows. We chose this software to design our platform. We use this platform to create our simulator rig which would hold all the components of the simulator kit. The components include steering, pedal/brakes, gearbox, etc.

9.1. Design of Parts of Structure in SolidWorks

Designing a CAD model of the hardware rig for a simulator in SolidWorks is a critical step in the development process. When designing a hardware rig for the simulator, it is essential to consider factors such as ergonomics, stability, and functionality. The SolidWorks software has been used to create a digital prototype of the hardware rig, which can be used to further test different configurations and make adjustments before building the physical prototype. Creating a detailed CAD model of the hardware rig in SolidWorks will help us ensure that the physical prototype is both functional and aesthetically pleasing and can help to streamline the manufacturing process by providing accurate specifications for each component. Figure 6.1 shows the prototype design of the hardware rig on which the components for the simulator would be fixed.

The design of simulator has been made in SolidWorks using square pipes. The gauge of pipes being used to design the kit is gauge 12. The model is being designed to withstand the minimal weight of 150 kg. The design of the simulator is shown below:

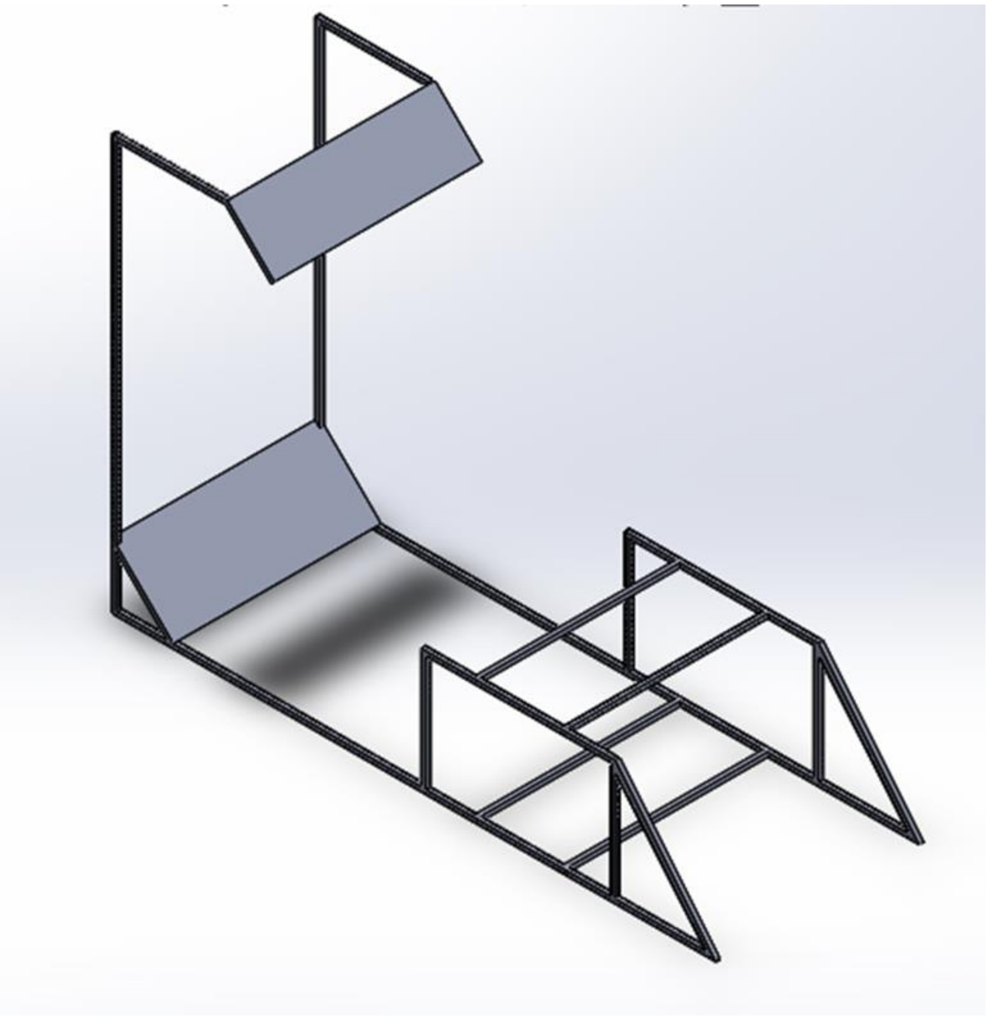


Figure 9.1: SolidWorks model of hardware rig

9.2. Dimensions

Dimensioning is a critical aspect of the design process in SolidWorks. It ensures the accuracy, clarity, and manufacturability of the 3D models. Dimensioning involves adding precise measurements and annotations to the model, providing essential information for manufacturing, assembly, and inspection. SolidWorks offers a comprehensive set of tools and features to create and manage dimensions effectively.

Dimensioning in SolidWorks involves specifying the size, shape, and location of features within a model. It enables designers and engineers to communicate design intent, provide critical measurements, and ensure the proper fit and function of the components. Before delving into the specific dimensioning tools in SolidWorks, it is essential to understand some fundamental concepts:

SolidWorks supports various dimension types, including linear dimensions, angular dimensions, ordinate dimensions, radius dimensions, diameter dimensions, and more. Each dimension type serves a specific purpose and provides unique information about the model.

SolidWorks allows users to specify the units for dimensions, such as millimeters, inches, or any other preferred unit system. Consistency in unit selection is crucial to avoid confusion and ensure accurate representation of the model.

Dimension precision refers to the number of decimal places or significant figures used in the dimensions. It is important to determine the appropriate precision based on the design requirements and manufacturing capabilities.

Linear dimensions are used to specify the size and location of straight edges, lines, or features within a model. SolidWorks provides several tools to create linear dimensions accurately:

The Smart Dimension tool allows users to select edges, lines, or points and automatically adds dimensions based on the selected geometry. It provides an intuitive and efficient way to dimension features.

Aligned dimensions are used when the dimension line does not align with the feature's edges. This type of dimension is particularly useful for complex geometries or skewed features.

Baseline dimensions are used to establish a baseline from which other dimensions can be referenced. This method simplifies dimensioning when multiple features share a common baseline.

Chain dimensions allow users to create a continuous set of dimensions along a series of features. This is useful for dimensioning patterns, arrays, or repetitive features.

Angular dimensions are crucial for specifying angles and rotations within a model. SolidWorks offers various tools for creating accurate angular dimensions:

The Angle Dimension tool allows users to specify the angle between two lines or edges within the model. It provides precise control over angular measurements.

The Smart Dimension tool can also be used to create angular dimensions by selecting two lines or edges and specifying the desired angle.

Ordinate dimensions are used to establish a reference dimension system based on a common origin. This type of dimensioning is particularly useful for complex geometries or irregularly shaped parts. SolidWorks provides an ordinate dimensioning tool that allows users to create dimensions relative to a base point or origin, simplifying the dimensioning process.

Radius and diameter dimensions are used to specify the size of circular features such as holes, fillets, or arcs. SolidWorks provides dedicated tools for creating radius and diameter dimensions:

The Radius Dimension tool allows users to select an arc or fillet and add a dimension that represents the radius of the circular feature.

The Diameter Dimension tool is used to specify the diameter of circular features. It can be applied to circles, cylinders, or rounded slots.

To ensure clarity and ease of understanding, it is important to follow best practices when dimensioning in SolidWorks:

Overcrowded dimensions can lead to confusion and difficulty in reading the drawing. Ensure that dimensions are placed strategically to minimize clutter and provide clear visibility of the model's features.

Place dimensions in a logical manner, considering the sequence of features, their dependencies, and the manufacturing process. This allows for easier interpretation and understanding of the model's intent.

Maintain consistency in dimensioning style throughout the model. Use the same precision, units, and dimensioning conventions to avoid confusion and misinterpretation.

Prioritize the dimensioning of critical or key features that directly affect the fit.

Prioritize the dimensioning of critical or key features that directly affect the fit, function, or assembly of the components. This ensures that essential dimensions are clearly communicated.

Redundant dimensions, which provide duplicate or unnecessary information, should be avoided. They can clutter the drawing and create confusion.

9.3. Tolerancing and Geometric Dimensioning and Tolerancing (GD&T)

SolidWorks provides tools to add tolerances and GD&T symbols to dimensions, specifying acceptable variations and geometric controls. Proper application of tolerances is crucial for manufacturing and ensures the functionality of the designed components.

SolidWorks offers advanced dimensioning options to further enhance the dimensioning process:

As mentioned earlier, baseline dimensioning allows users to establish a baseline and reference subsequent dimensions to it. SolidWorks provides tools to create and manage baseline dimensions efficiently.

Users can control the position and orientation of the ordinate dimensioning origin to align with specific design requirements. This flexibility enables precise dimensioning in complex geometries.

SolidWorks allows users to customize the display of dimensions, including font styles, arrow styles, leader line styles, and text alignment. These options allow for improved readability and visual aesthetics of the dimensioning.

Dimensions in SolidWorks can be defined as either driving or driven. Driving dimensions are used to control the geometry, while driven dimensions are calculated based on the driving dimensions. This feature ensures the parametric nature of the model and maintains associativity between dimensions and features.

In addition to aiding design and communication, dimensioning in SolidWorks is crucial for manufacturing and documentation purposes:

Accurate and clear dimensions facilitate the machining process by providing the necessary measurements for material removal, hole drilling, or profile cutting.

Dimensions play a crucial role in assembly instructions and documentation. Clear and precise dimensioning ensures proper alignment and fit of components during assembly.

Dimensioned drawings provide the necessary information for inspection and quality control processes. Inspectors can reference the dimensions to verify the manufactured parts' conformance to design specifications.

Dimensioning in SolidWorks allows for easy design iteration and modification. By associating dimensions with features, changes to dimensions automatically propagate throughout the model, enabling efficient design modifications.

Dimensioning Considerations for Specific Design Features

Certain design features require special attention when dimensioning in SolidWorks:

When dimensioning patterns or arrays of features, it is important to provide clear indications of the pattern's intent, such as the spacing, number of instances, or overall size.

For threaded features or fasteners, it is common to use thread callouts or industry-standard symbols to specify the thread size, pitch, and type.

When dimensioning sheet metal parts with bends, it is important to specify the bend radius, bend angle, and bend direction to ensure accurate fabrication.

It is crucial to adhere to relevant dimensioning standards when using SolidWorks for design and documentation. Standards such as ISO, ANSI, ASME, or company-specific standards provide guidelines on dimensioning practices, including dimension styles, symbols, and tolerances. Adhering to these standards ensures consistency, compatibility, and ease of interpretation across different design teams, manufacturers, and suppliers.

In conclusion, dimensioning in SolidWorks is a critical aspect of the design process, enabling accurate communication, manufacturability, and documentation of 3D models. SolidWorks offers a comprehensive set of dimensioning tools and features that allow designers and engineers to specify precise measurements, tolerances, and geometric controls. By following best practices, utilizing advanced dimensioning options, and adhering to relevant standards, users can effectively dimension their models for manufacturing, assembly, inspection, and design iteration purposes.

Dimension is the most important part of drawing. The rig is designed by a series of features in SOLIDWORKS and each feature is designed by a sketch and the dimensions of the sketch are shown below:

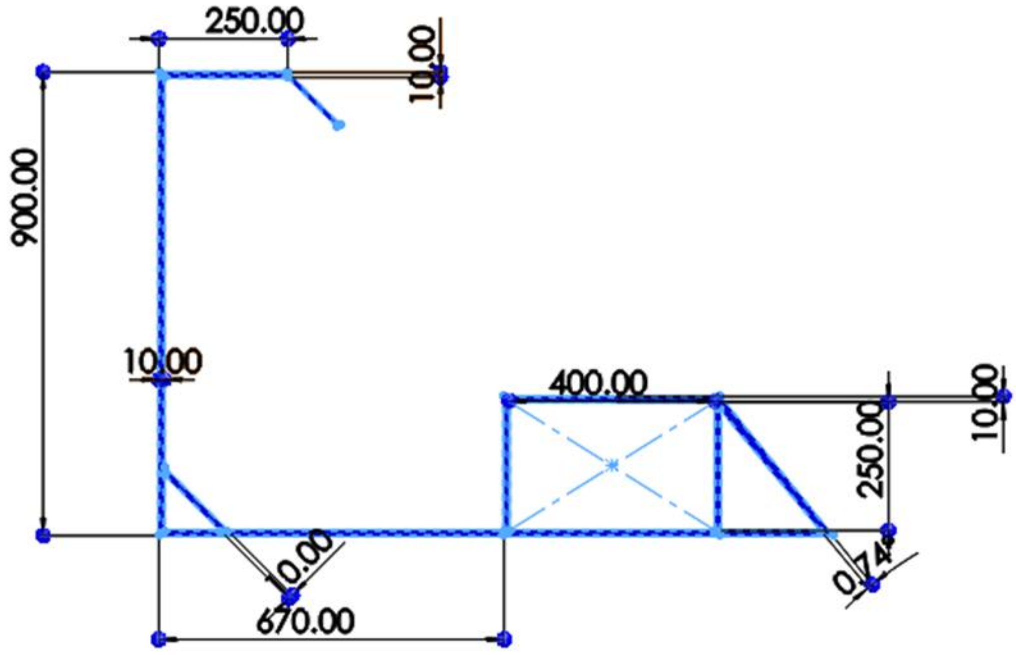


Figure 9.2: Dimensioned diagram of the model

9.4. **Ansys Simulation**

The Ansys simulation is being performed on the rig. The analysis is done on the static structural to check that how much load it can withstand.

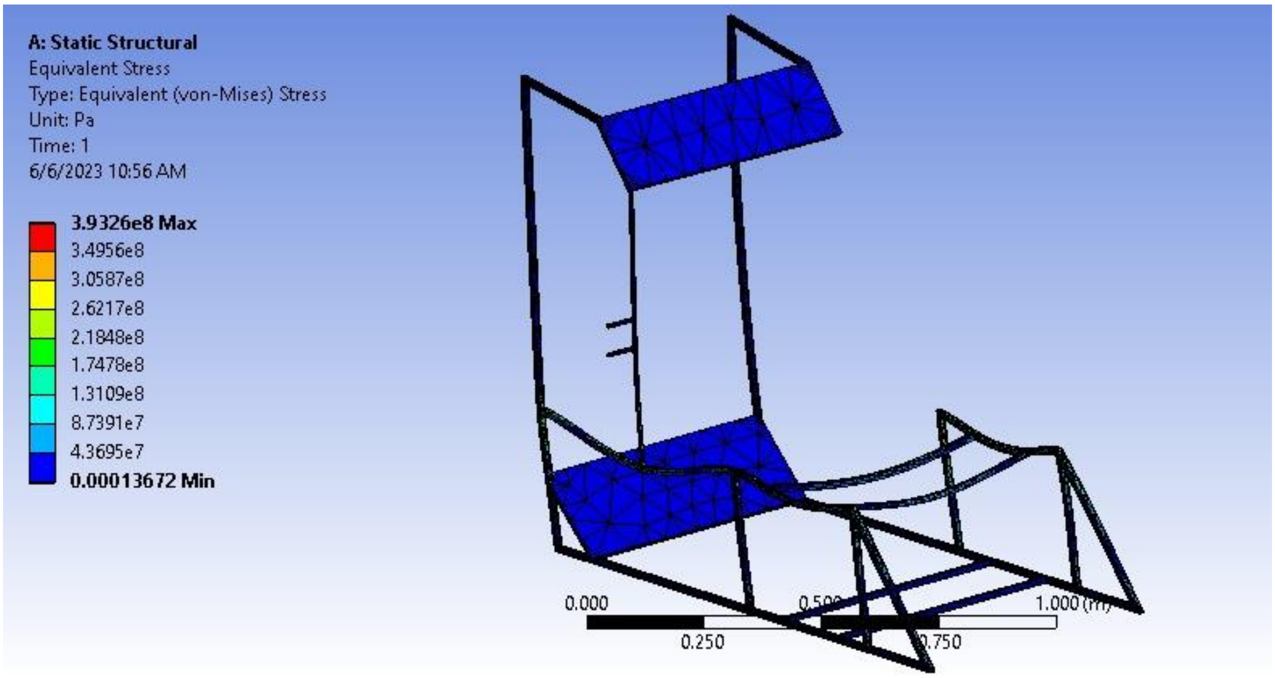


Figure 9.3: Static structural analysis of rig

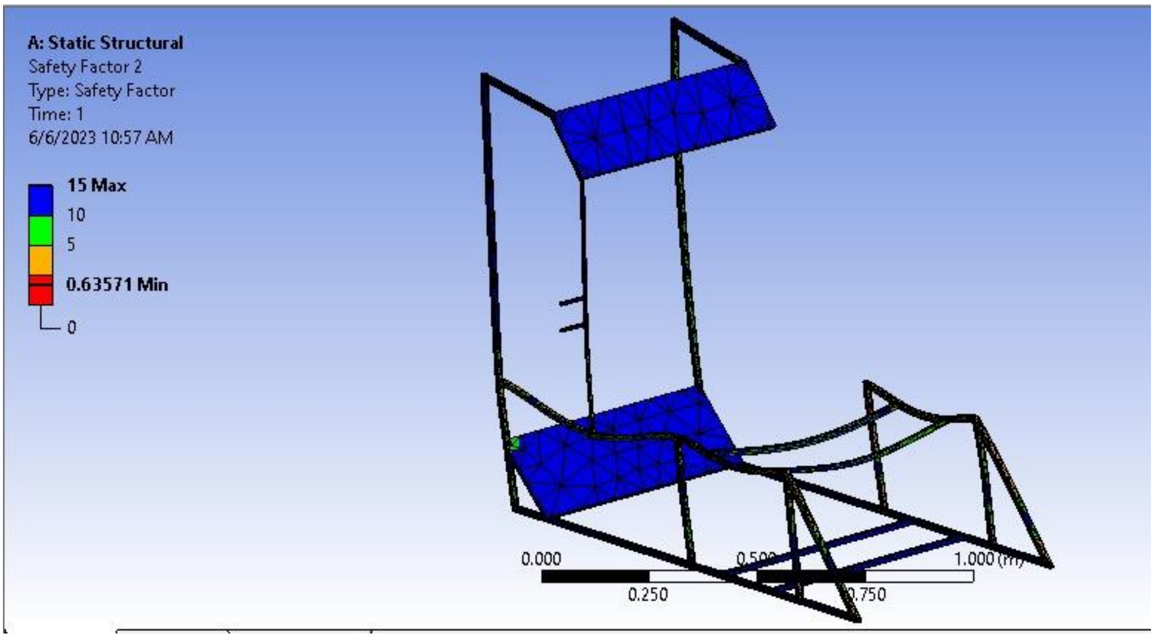


Figure 9.4: Safety factor

9.5. Complete Design of rig

A car simulator rig is a device that allows users to experience the sensation of driving a car without actually being in a car. It typically consists of a seat, a steering wheel, pedals, and a visual display that shows the road ahead. Car simulator rigs are used for a variety of purposes, including training drivers, testing new car designs, and playing racing games.

To design a car simulator rig in SolidWorks, you will need to understand the following concepts:

Structural analysis: This is the process of determining how a structure will behave under different loads. It is important to perform structural analysis on a car simulator rig to ensure that it is strong enough to support the weight of a person and withstand the forces generated during simulated driving.

Material selection: The material you choose for the frame of the car simulator rig will affect its strength, stiffness, and weight. Steel is a common choice for car simulator rigs because it is strong, durable, and relatively inexpensive.

Load capacity: The load capacity of a car simulator rig is the maximum weight it can safely support. You will need to determine the load capacity of your rig based on the weight of the heaviest person who will be using it.

Safety factors: Safety factors are used to account for uncertainties in the material properties, manufacturing processes, and loading conditions. A safety factor of 1.5 means that the rig must be able to support 1.5 times the maximum weight it is designed for.

Ergonomics: Ergonomics is the study of how people interact with their environment. When designing a car simulator rig, it is important to consider the ergonomics of the user interface. The seat, steering wheel, and pedals should be positioned in a way that is comfortable and natural for the user.

Sustainability: Sustainability is the practice of using resources in a way that meets the needs of the present without compromising the ability of future generations to meet their own needs. When designing a car simulator rig, you can incorporate sustainable design principles by using recycled materials, energy-efficient components, and water-saving practices.

Manufacturing and assembly: The manufacturing and assembly of a car simulator rig will depend on the design and materials used. Steel car simulator rigs are typically welded together, while aluminum car simulator rigs are typically bolted together.

Testing and validation: Once the car simulator rig is designed, it is important to test it to ensure that it meets all the requirements. This may include static load testing, dynamic load testing, and user testing.

Documentation: Accurate and comprehensive documentation is essential for the maintenance and repair of a car simulator rig. The documentation should include drawings, assembly instructions, and material specifications.

By following these principles, you can design a car simulator rig that is safe, comfortable, and durable.

Here are some additional considerations for designing a car simulator rig:

The type of driving experience you want to provide: Do you want the user to be able to experience the sensation of driving on a variety of different roads, or do you want to focus on a specific type of driving, such as racing?

The budget you have available: Car simulator rigs can range in price from a few hundred dollars to several thousand dollars.

The level of realism you want to achieve: Some car simulator rigs are very realistic, while others are more basic.

Once you have considered these factors, you can start designing your car simulator rig. With a little planning and effort, you can create a rig that provides an immersive and enjoyable driving experience.

Chapter 10: Limitations

10.1. Simplified Modeling

The simulator and the virtual model are based on elementary vehicle dynamics and engine data and is based on some assumptions. There are some factors that could not be added to the model due to limitations of time, computational power, research gap, or availability of data. The model may not capture all the complexities and nuances of real-world driving conditions and vehicle behaviors. However, we tried to add all the necessary factors involved in studying the longitudinal performance of a vehicle and fuel consumption parameters.

10.2. Simulator Effect

No matter how realistic the simulator is, the experience of driving an actual car in the real world cannot be fully recreated in a virtual environment. Factors like traffic, weather patterns, and road conditions affect driving patterns and therefore the driving patterns recorded in the simulator are not as accurate as we would want.

10.3. Hardware Limitations

The Logitech input devices we are using are top of the line and they mimic the mechanical controls of the car, but the translation of the mechanical systems into electrical devices are not ideal and driving experience is affected. Moreover, there are certain losses in actual cars which are hard to predict accurately and can only be approximated.

10.4. Parasitic Loads on the Engine

There are some accessories in vehicles that increase load on the engine during operation. These include Air Conditioners, Superchargers, Fans, etc. When an AC is turned on in a car, it generally consumes more fuel, however the exact impact depends on factors like outside temperatures, condition of the AC, exhaust emissions, and engine power. These kind of load effects could not be included in the simulator model.

Chapter 11: Applications

The vehicle longitudinal performance simulator provides a virtual platform to assess driving methods of drivers in terms of fuel efficiency by recreating a realistic model of the vehicle. This simulator represents an accurate model of the dynamics of the vehicle as well as the engine model. Moreover, users can define a number of parameters in the simulator as per their needs to experience a more realistic and relevant simulation. Some of the applications of our simulator are given below:

11.1. Economic Driving Practices

Fuel efficiency is a major part of our research. Our simulator serves as a tool for teaching fuel efficient driving methods to its users. To save on fuel consumption, we need to assess and correct our driving methods. The simulator can assist drivers in learning how to drive vehicle efficiently by giving real-time feedback during the simulation and statistics of the drive cycle to show the driver how they can improve their fuel efficiency through better driving practices.

11.2. Research & Development

The virtual environment in the simulator can be used to perform experiments and research that are otherwise too costly or inconvenient to perform in real life. The simulator is made such that it can be adjusted and modified for any vehicle or engine type. This fact is useful for comparing different vehicles on a similar drive cycle and analyzing their performance [21]. Developers can use this data to create more sustainable and better performing vehicles without going through the extensive hassle of experimenting on actual engines and iterating each parameter separately.

11.3. Safety Testing

Car developers go through extremely difficult and dangerous testing procedures to benchmark the limits of their machines. This simulator has the advantage that it mimics the whole vehicle without real-life hinderances. This means that we can focus on any given factor of interest and test it to its extremes without worrying about other affecting factors. For example, we can test the maximum suspension that can be fitted in a vehicle without causing rollover of the vehicle at a given speed and steering angle.

11.4. Education and Public Awareness

The simulator can serve as an educational tool to raise public awareness about the impact of driving behavior on fuel consumption and emissions. The attractive interface and game-like feel of the simulator makes people want to try the demo. It can be integrated into educational programs, exhibits, and public campaigns to promote eco-friendly driving practices and sustainability in the transportation sector.

11.5. Autonomous Vehicle Development

The simulator can be adapted for use in the development and testing of autonomous vehicles. By simulating different driving scenarios and behaviors, autonomous vehicle algorithms can be optimized for energy efficiency, leading to reduced fuel consumption and emissions in self-driving vehicles. In automatic transmission cars, the ideal gear changing schedule for economic driving can be derived from the simulator model [22].

Chapter 12: Conclusion & Future Prospects

12.1. Conclusion

The project, Development of a vehicle longitudinal performance simulator, is a vehicle simulator with realistic engine and vehicle physics aimed at saving fuel consumption in actual vehicles. Firstly, the simulator was designed in Unity 3D to represent a realistic version of an actual car and give accurate results. Furthermore, the integration of a MATLAB engine model with the simulator allowed for validation and comparison of drive cycles against ideal driving methods. This integration provided valuable data on fuel consumption, engine performance, and other relevant metrics.

By exploiting the capabilities of this simulator and its integration with hardware, the research project successfully contributed to the ongoing efforts of achieving better longitudinal performance in vehicles while promoting energy savings. The findings of this study can be used to inform the development of future vehicles and guide improvements in driver training and education for sustainable and economical driving practices.

12.2. Future Prospects

12.2.1. Application in Actual Vehicles

Taking this idea ahead, we can use the research carried out for building the simulator and driver training system and use it to assist drivers in actual vehicles. The simulator can be turned into an emulator, i.e. a small device that can be fitted into the ECU of any vehicle and read its data like engine RPM, vehicle speed, load on the engine, sensor outputs, etc. This data can then be used to assist drivers in changing gears at the appropriate time and using correct braking and throttling methods.

12.2.2. Virtual Dynamometer

Moreover, the simulator can be employed in engine testing labs as a virtual dynamometer to design and diagnose engines for better performance and economy. A car developer would not need to create an entire engine and a vehicle to go with it to test a concept he has in his mind. Instead, the vehicle performance simulator can be adjusted to match the specifications of the desired engine and vehicle and tested on the rig provided. This can lead to much more efficient engine testing and development.

12.2.3. Integration with Autonomous Vehicles

With the increasing trend towards advancement of autonomous vehicle technology, the simulator can be adapted to train and optimize the driving algorithms and behavior of self-driving cars. By simulating different scenarios and optimizing decision-making processes, autonomous vehicles can be programmed to operate in the most energy-efficient manner, reducing fuel consumption and emissions on a larger scale. Of course, we would need to add obstacles like traffic and pedestrians in the simulator for that kind of usability.

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