

ADAMA SCIENCE AND TECHNOLOGY UNIVERSITY

SCHOOL OF MECHANICAL, CHEMICAL AND MATERIALS ENGINEERING



The Effect of Tyre Inflation Pressure on Fuel Consumption and vehicle Handling Performance a case of ANBESSA CITY BUS

A thesis submitted in partial fulfillment of the requirements for the award of the Degree of
Master of Science in Automotive Engineering

By

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MECHANICAL SYSTEMS AND VEHICLE ENGINEERING PROGRAM

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Adama-Ethiopia

CANDIDATE'S DECLARATION

I hereby declare that the work which is being presented in the thesis titled “The Effect of Tyre Inflation Pressure on Fuel Consumption and vehicle Handling Performance a case of ANBESSA CITY BUS” in partial fulfillment of the requirements for the award of the degree of Master of Science in Automotive Engineering is an authentic record of my own work carried out from October 2016 to up June 2017, under the supervision of N. RAMESH BABU Department of Mechanical and Vehicle Engineering, Adama Science and Technology University, Ethiopia.

The matter embodied in this thesis has not been submitted by me for the award of any other degree or diploma. All relevant resources of information used in this thesis have been duly acknowledged.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief. This thesis has been submitted for examination with my approval.

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Performance a case of ANBESSA CITY BUS**

By

Nigatu Belayneh

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External Examiner	signature	Date

Dedication

To my Family

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ACRONYMS AND ABBREVIATIONS

RR, T	Tyre rolling resistance
RR, Tr	Road rolling Resistance
RR, S	Resistance due to tyre slip angle
FR, fr.	Resistance due to bearing friction and residual braking
E_{tract}	Total tractive energy,
ε	Drivetrain efficiency,
P_{acc}	Average accessory power
t	Time travel.
C_{sr}	Static Coefficient
C_{dr}	Dynamic Coefficient
F_R	Rolling resistance force
μ_r	Rolling friction coefficient
P	Tyre inflation pressure
Fz	Normal Load
P_{used}	Brake power used
F_{Dmodel}	Total drag force
V_{bus}	Velocity of the bus (m/s)
L	Load carrying capacity
S	Tyre section width
D_R	Nominal rim diameter
K_Z	Tangent Stiffness - kg/mm
W	Tyre footprint width – mm
OD	Outside diameter – mm
F_Y	Lateral Force,
F_X ,	Longitudinal force,
$C\alpha$	Cornering stiffness
C_k	Cornering stiffness

α	Slip angle
Cd	Drag coefficient (CD)
Fd	Lifting force
mph	mile per hour
lit/km	Liter per kilometer

ABSTRACT

It is necessary to minimize vehicle power losses to improve efficiency. The inflation pressure of tyres has great influence on power loss due to rolling resistance. This work aimed to investigate the effect of inflation pressure of tyre on fuel consumption and vehicle handling performance. This work is done based on the specifications and study done on Anbessa city bus. Three vehicle tyre models are built in different range of inflation pressure in CATIA. The models were analyzed for aerodynamic drag and lift forces using phoenix software. The specifications of the tyre P295/80R225 which is used in Anbessa city bus were taken for building models. The load on the tyres, rolling resistance variations and the rotational aerodynamic effect of tyre are used as inputs among other parameters to analyze the fuel consumption. From the analysis it is found that in case of model 3, which is under inflation, the fuel consumption was 0.378 lit/km on average which is about 11.05% more than model 1 with recommended inflation pressure with speed of 60 km/hr. and same distance travelled. It is also observed that the fuel consumption decreased by 9.74 % when the tyre pressure was increased from the recommended pressure of 0.83Mpa to 0.9Mpa at a given speed and distance. In the case of handling performance the bus requires more steering effort to maintain the turning way for the under-inflated tyre, in model 3 up to 9000 N is need at the slip angle of 8° . The maximum bus tyre slip angle, $\alpha = 8^{\circ}$ also increased due to the bus's reduced directional handling capabilities when equipped with under-inflated tyres.

Keywords: Rolling resistance, tyre model, mathematical model, aerodynamic drag, lift force, fuel consumption, vehicle handling.

CHAPTER ONE

INTRODUCTION

1.1. Introduction about Tyre Inflation

The tyre inflation pressure plays an increasingly important role in the vehicle performance and fuel economy of road. However, this status is achieved because of more than one hundred years' tyre evolution since the initial invention of the pneumatic tyre by John Boyd Dunlop around 1888. Tyres are required to produce the forces necessary to control the vehicle. As we know that the tyre is the only means of contact between the road and the vehicle but they are at the heart of vehicle handling and performance. The relationship between human and tyre and environmental surrounding play an important role for developing of tyre technology. These concerns include traffic accidents caused by tyre failure, the waste of energy due to bad tyre conditions, the pollution through the emission of harmful compounds by tyres, and the degradation of road surfaces related to tyre performance, etc. [12].

Tyre as one of the most important components of vehicles requires to fulfill a fundamental set of functions are to provide load-carrying capacity, to provide cushioning and dampening against the road surface, to transmit driving and braking torque, to provide cornering force, to provide dimensional stability, to resist abrasion. There are various losses associated with the vehicle that affect its fuel economy as it is being operated. These losses include engine, driveline, aerodynamic and rolling losses, while the rolling loss is associated with the vehicle tyres [3].

Nowadays, when car companies are trying to reduce fuel consumption and lower CO₂ emission, aerodynamic design of cars and its components plays important role. According to different sources even up to 25% of the car aerodynamic drag comes from wheels. Car manufacturing companies and tyre manufacturers are facing problems connected with reduction of friction coefficient as well as improving air flow around the tyre and whole car body. It is clearly visible that this branch of car design can give benefits connected not only with reduction of fuel consumption and CO₂ emission, but also with safety and comfort of modern vehicles [4].

The easiest way to reduce CO₂ emissions in a vehicle is to reduce its fuel consumption since the CO₂ emission is directly proportional to the amount of fuel consumed.

Tyre inflation pressure plays an important role in the vehicle's fuel consumption. The results of a survey released by the US Department of Transportation's NHTSA (National Highway Traffic Safety Administration) in 2001 showed that a decrease of 0.55 bar, from the recommended inflation pressure, resulted in the reduction of fuel efficiency by 3.3%, in miles per gallon [6]

1.2. Background

This work is initiated by myself to investigate the influence of various tyre inflation pressure on ADDIS ABABA city bus in collaboration of fuel consumption and its handling performance. Related work is a pre-study to a project initiated by Ivar Frischer, Chief Design Engineer at Yovinn AB, in collaboration with the Centre for ECO Vehicle Design at KTH The Royal Institute of Technology. The idea is to develop an on-board adaptive Tyre Pressure Regulating System (TPRS) for passenger cars that is capable of continuously varying an optimized amount of air in the tyres based on different driving conditions such as road quality and driving styles [6].

The inflation pressure indirectly affects the side wall stiffness and foot-print of the tyre which play an important role in determining vehicle handling and ride characteristics. Numerous tests have also shown significant fuel consumption benefits obtained by simply maintaining appropriate tyre pressure in all wheels [5]. According to the Rubber Manufacturer's Association, when a tyre is under inflated by one pound per square inch (psi), the tyres rolling resistance is increased by approximately 1.1% and that a five to eight percent deterioration in rolling resistance performance, which equates to a roughly one percent reduction in fuel efficiency [Calwell et al., 2003]. This is similar to the review study done by Schuring and Futamura that found for each ten percent reduction in the rolling resistance coefficient the fuel efficiency increased by (1.2–2.5)% for city and (0.9–2.1)% percent for highway driving [Schuring and Futamura, 1990]. This is because inflation pressure determines tyre stiffness, which has a significant influence on the contact area of the tyre and pressure distribution over the contact surface. Thus, as pressure in the vehicles tyres is reduced, the rolling resistance increases over the road because the surface contact area and virtual hill height is increased. When the rolling

resistance is increased, it takes more energy (fuel) to get the automobile to go the same distance. The relationship between tyre pressure, rolling resistance and fuel economy is complex and dynamic and is dependent on several other factors, including vehicle type and load, road and environmental conditions [5].

Another work connected with automobile wheels was made by [6] whose investigation focused on identification of vortices in case of rotating wheel, while jetting effect was widely described by P. Leśniewicz¹, M. Kulak and M. Karczewski Institute of Turbo machinery, Lodz University of Technology, Poland. The importance of vortices located near the area of contact between the tyre and the ground was highlighted. As a result, the flow phenomena described among others, shed light at the importance of analyzing vehicle aerodynamics with inclusion of rotating wheels, both experimentally and numerically, a practice that before 1990s was quite seldom. However, still a number of publications strictly connected with investigation of tyre geometry using Computational Fluid Dynamics (CFD) in synergy with experiment are limited.

1.3. Problem Statement

In our country there is no much attention given to the safety of the vehicle and usage of fuel. There is wastage of fuel due to many internal and external reasons. Internal reasons like mechanical loss and external factors like road, overloading beyond recommended capacity. The other important factor for fuel wastage is tyre inflation pressure, which is due to the negligence of driver or mechanics. One of the important factors determining vehicle dynamics including safety, vehicle handling and fuel consumption is tyre air pressure. A reduction or increased in tyre pressure from the proper or recommended level will cause deteriorations in the driving stability, fuel consumption, tyre life, and possible bursts of the tyres.

Regardless of its size, every tyres load capacity, durability, traction and handling is dependent on using the recommended inflation pressure for the application. Since both too little and too much inflation pressure sacrifices some of the tyres performance and vehicle handling.

Underinflating or overloading leads to rapid wear on each side of the tread and internal damage to the casing. Whereas overinflating wears the center of tread. The major causes of over-inflation are an inaccurate tyre pressure gauge, hot tyres or incorrect reading by the operator.

If tyre pressure is too high, the tyre contact patch is reduced, which decreases rolling resistance. However, ride comfort is reduced, but traction is not always reduced, stopping distance is not always increased.

If tyre pressure is too low, the tyre contact patch is increased, increasing rolling resistance, tyre flexing and friction between the road and tyre. This "underinflating" can lead to tyre overheating, premature tread wear, and tread separation in severe cases.

The problem is how far vehicles deviate from the recommended tyre pressure and the relationship between the tyre pressure and fuel consumption and vehicle handling performance.

1.4. Research Objective

1.4.1. General objective

- The general objective of this thesis work is to investigate the effect of tyre inflation pressure on fuel consumption and vehicle handling performance.

1.4.2. Specific objectives

- To study existing tyre of ANBESA CITY BUS and tyre usage.
- To model the tyre with different inflation pressure.
- To investigate the effect of inflation pressure on fuel consumption.
- To investigate the effect of inflation pressure on stability of the vehicle.

1.5. Significance of Research

Modern automotive world is focusing on ways how to obtain higher efficiency of vehicle in the fuel consumption to minimize emission and in better handling performance to improve comfort. Many new technological advancements target power consumption, but one of the easiest ways to increase efficiency often goes ignored: the vehicle's tire pressure [10]. From research, when tyre pressures of vehicles fall below the recommended tyre pressure more fuel are consumed. This means that when vehicles have their tyre pressures below the recommended drivers will spend more money on fuel.

So significantly this work focus in our country ANBESA CITY BUS is widely used bus in public services also for governmental service its tyre inflation pressure can affect the fuel

imported and the bus smoothly running performance. In the work we can investigate the effect of tyre inflation on bus and to develop tyre model.

To study the impact of tyre pressure on vehicle performance and fuel consumptions, vehicle models need to be developed. The tyre models used in these vehicle models should be able to capture and simulate the effects of tyre pressure on the vehicle's lateral, longitudinal and vertical response.

To develop Numerical model prepared for this investigation was able to predict major flow characteristics connected with aerodynamic analysis of tyre inflation pressure in each range (under-inflation and over-inflation). The most important differences between flow around the tyre in under-inflation and over-inflation and the smooth tyre were identified not only in terms of drag coefficient but also pressure distribution.

Due to inappropriate fuel consumption the government has to import more crude oil and that means more money has to be invested into road transportation sector of the economy. If that happens, other sectors of the country will not be developed. There for this study shows how to minimize the fuel consumption using recommended tyre inflation pressure.

1.6. Scope of Research

In this project work the fuel consumption and vehicle handling performance is affected by the inflation of tyre with in rolling resistance losses in a different tyre pressure range, the rotational aerodynamic effects of tyre and contact stress deformation, cornering properties connecting with lateral force are studied and modeled to estimating the fuel consumption of ANBESA CITY BUS it locally used and maintenance service in Addis Abeba lead by Anbessa city bus association.

The influence of tyre pressure on vehicle handling is studied on dry surfaces, at different velocities and pressures settings in the four tyres. The impact of factors such as tyre tread design, tread depth, standing water height, road surface roughness etc. on tyre force and moment characteristics, are not modeled explicitly.

The influence of inflation pressure on vehicle's ride characteristics is evaluated at different inflation pressures and compared to the vehicle whose tyres are at the nominal inflation pressure.

1.7. Limitation

This thesis limitations are

- The effect of temperature on viscoelasticity and inflation pressure is not considered because of lack of automatic tyre pressure and temperature monitoring system
- Longitudinal forces and moments have not been analyzed for handling performance because of lack of adequate knowledge on software's like MATLAB SIMULINK
- The inertia developed on the bus during cornering is not considered because of lack of ESP (Electronic stability program) sensor on the buses

1.8. Anbessa city bus association

ANBESA CITY BUS Association company is focusing on ways to obtain higher efficiency of vehicle on the fuel consumption to minimize emission by fuel consumption control and better handling performance means comfort.

ANBESA CITY BUS specifications are

- It has 65 seat
- Consume 25 liter fuel per 100km.
- Overall weight
- Tyre type used

Know other ways to increase efficiency often goes ignored: the vehicle's tire pressure. Therefore the proposed studying of the effect of Tyre inflation pressure on Fuel Consumption and vehicle Handling performance, Simulation and Modeling on case of ANBESA CITY BUS can investigate the effect to improve the bus efficiency and quality.

CHAPTER TWO

LITERATURE REVIEW

2.1. Introduction to Tyre

Tyre is a covering mounted on the rim of a wheel that serves as a cushion and surface for traction. Tyres are used on road vehicles, tractors, aircraft and spacecraft landing gear, factory and warehouse machinery, and on a variety of other vehicles, including shopping carts and baby carriages. Tyres are made of chemically treated rubber and fabric. Those for indoor use are generally solid rubber with a smooth surface, while those used outdoors are pneumatic, or hollow and filled with pressurized air, and have a traction pattern cut into the surface.

The pneumatic tyre plays an increasingly important role in the vehicle performance of road. However, this status is achieved because of more than one hundred years' tyre evolution since the initial invention of the pneumatic tyre by John Boyd Dunlop around 1888. Tyre are required to produce the forces necessary to control the vehicle. As we know that the tyre is the only means of contact between the road and the vehicle but they are at the heart of vehicle handling and performance. The inflated rubber structure provides comfortable ride for transportation. With the growing demand for the pneumatic tyre, many improvements have been made based on the initial conception, such as the reinforcement cords, the beads, the vulcanization, the materials and the introduction of the tubeless tyre. The relationship between human and tyre and environmental surrounding play an important role for developing of tyre technology. These concerns include traffic accidents caused by tyre failure, the waste of energy due to bad tyre conditions, the pollution through the emission of harmful compounds by tyres, and the degradation of road surfaces related to tyre performance, etc. [12].

2.1.1. The contribution of tyre on the vehicle's

The influence of tyre pressure on parameters that affect vehicle fuel consumption, handling behavior and ride characteristics are also discussed.

There are several factors that contribute to the overall fuel consumption of a vehicle. In general, these factors may be broadly classified into the following categories:

- Energy loss from tyres,
- Aerodynamic drag losses,
- Vehicle inertia during acceleration or deceleration.

Energy losses also arise from the vehicle driveline components and auxiliary devices. However, this report will only shed light on the losses from the tyres and the affect it has on the overall fuel consumption of the vehicle. Some of the main parameters affecting RR are discussed in the sections below [6].

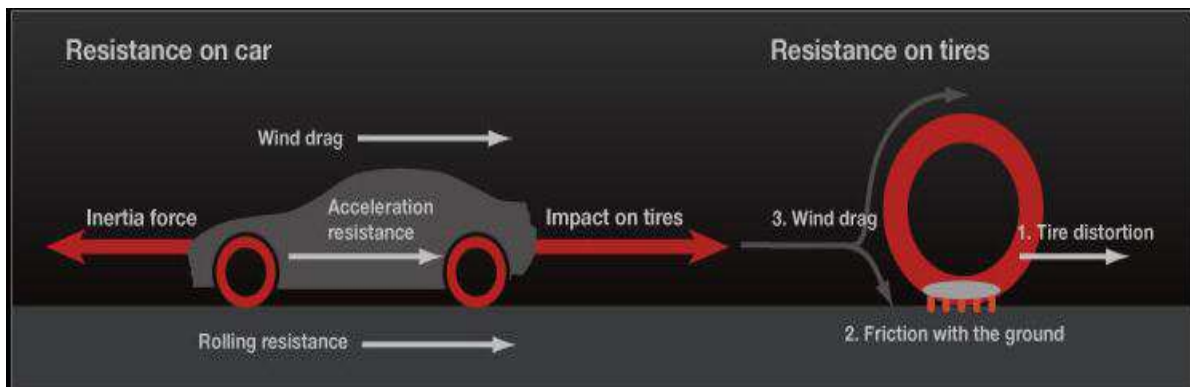


Figure 2.1 Resistance on a car

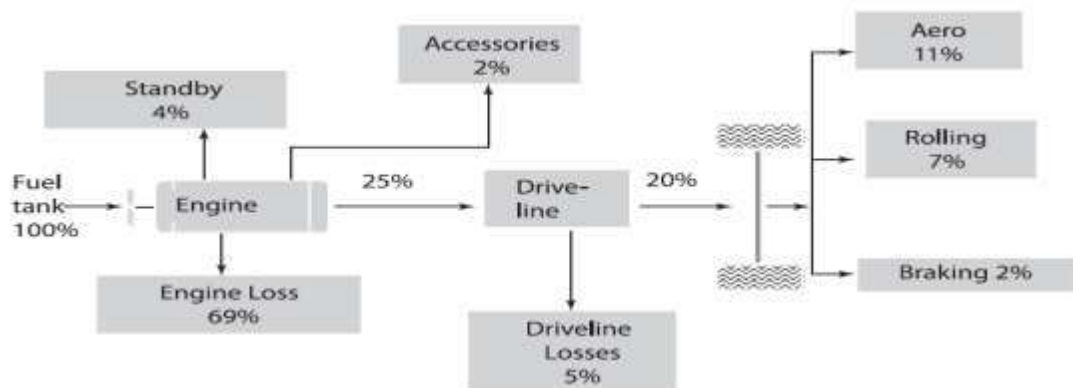


Figure 2.2 Energy flows for a late-model midsize passenger car highway driving.

2.1.2. Tyre parts and contraction

Tyre provides the force which affects the dynamics and performance of a vehicle, in terms of acceleration, braking, ride and steering. When a vehicle is driven on the road, the only part of the vehicle that comes in contact with the road is the tire. Hence, it is important to understand how a tyre behaves to various road inputs. The focus area of this research is to determine the effects of tyres inflation pressure in order to improve fuel economy, vehicle safety and performance. Studying the different parts of a tyre is necessary to see how they influence fuel economy related with rolling resistance and vehicle ride and safety [9].

The casing often called the carcass is the structural frame of the tyre. It usually consists of directionally oriented cords banded together by rubber into layers, called plies, which give the tire strength and stiffness while retaining flexibility. The number of plies is determined by tire type, size, inflation pressure, and intended application.

Plies oriented mainly from side to side are “radial,” while plies oriented diagonally are “bias.” In the area where the tread is applied, the plies in the radial casing are usually covered by a relatively stiff steel belt or a steel belt covered by a circumferential nylon cap ply. The steel belt is made by using fine wire twisted into cables as cords. For the inflated tire to be retained on the wheel rim, the plies are anchored around circumferential hoops made of multiple strands of fine, high-tensile wire located at the inner edges of the two sidewalls where they mate with the rim. These two hoops, called beads, are pressed against the rim flange by inflation pressure, thereby seating and sealing the tire on the rim. Encircling the tire is the tread. This is a thick band of rubber that forms the tire surface, from its crown (its largest radius) to its shoulders (the areas in which the tread transitions to the sidewalls) [13].



(a) Bias tyre.



(b) Radial tyre

Figure 2.3: Difference between bias and radial tyres.

The tyre construction, such as aspect ratio, belt construction and tread compound, depends on the size and target market (speed rating). This information is printed on every tyre, e.g., 215/55 R 16 97 V. The first number (215) is the nominal section width in mm, the second number (55) is the percentage of the height/width ratio of the cross-section. The R (radial) stands for the tyre construction code. Then the rim diameter (16) is given in inches and 97 is the load capacity index, which indicates the maximum load capacity. The last symbol (V) is the speed symbol, which stands for the maximum speed [13].

Tyre model developed on this thesis to investigate the Fuel consumption reduction by tyre drag optimization and handling performance on ANBESSA CITYBUS is a research project aiming to propose effects of tyre inflation pressure from the recommended range based on utilizing scientific methodology combined with the existing expert knowledge. The current practice for selection of the tyres' configuration at Anbessa bus is usually based on experience and customers' input. Nowadays, the competition between heavy duty vehicle manufacturers requires an improved method for selecting the optimal set of tyres for particular vehicle-operating environment combination.

2.2. Effects of Tyre Pressure on Vehicle Performance

Tyres are specified by the vehicle manufacturer with a recommended inflation pressure, which permits safe operation within the specified load rating and vehicle loading. For passenger vehicles and light trucks, the tyres should be inflated to what the vehicle manufacturer recommends, which is usually located on a decal just inside the driver's door, or in the vehicle owners handbook. Tyres should not be inflated to the pressure on the sidewall; this is the maximum pressure, rather than the recommended pressure.

If tyre pressure is too high, the tyre contact patch is reduced, which decreases rolling resistance. However, ride comfort is reduced, but traction is not always reduced, stopping distance is not always increased. Also, going above max sidewall pressure rarely results in the center of the tyre wearing more than the shoulder. If tyre pressure is too low, the tyre contact patch is increased, increasing rolling resistance, tyre flexing and friction between the road and tyre. This "under inflation" can lead to tyre overheating, premature tread wear, and tread separation in severe cases. Braking distance does not statistically change as tyre pressure increased, suggesting that a

larger contact patch from under inflation may not be a significant contributor for the conditions explored in these specific tests [5].

2.3. Influence of the tyre rolling resistance to fuel consumption

2.3.1. Rolling Resistance (RR)

Rolling resistance is the resistance to rolling caused by deformation of the tyre in contact with the road surface. As the tyre rolls, tread enters the contact area and is deformed to conform to the roadway. The energy required to make the deformation depends on the inflation pressure, rotating speed, and numerous physical properties of the tyre structure, such as spring force and stiffness. Tyre makers seek lower rolling resistance tyre constructions in order to improve fuel economy in cars and especially trucks, where rolling resistance accounts for a high amount of fuel consumption.

The rolling resistance of a wheel (RR) is made up of four components. Tyre rolling resistance depends up on the following parameters [12]. The sum of these components is equal to the total rolling resistance.

$$RR = FR, T + FR, Tr + FR, S + FR, fr \dots\dots\dots 2.0$$

Components such as

- Tyre rolling resistance (FR, T),
- Road rolling Resistance (FR, Tr)
- Resistance due to tyre slip angle (FR, S)
- Resistance due to bearing friction and residual braking (FR, fr).

Tyre rolling resistance is defined as the force required to maintain the forward movement of a loaded pneumatic tyre in a straight line, on a flat road, at a constant vehicle speed when no wind resistance is present. The tyre losses may be attributed to three broadly classified mechanisms.

- I. Friction or scrubbing between tyre and roadway,
- II. Aerodynamic drag of the rolling wheels,
- III. Hysteretic loses of tyres due to cyclic stressing of the rubber compound.

Friction or scrubbing losses occur due to slippage at the tyre-road interface due to tangential forces and due to the difference in the Young's modulus and radii of curvature of rolling bodies in contact, resulting in shear tension and causing shear friction. However, scrubbing has low

impact on the Rolling Resistance as it has been found to be hardly affected by lubrication of the surfaces in contact [6]. Though not much of the wheels are exposed in the direction of travel for a passenger car, the aerodynamic drag from the wheels can vary considerably based on the overall design of the tyre carcass and wheel hub. However, under normal operating conditions, majority of the tyre loss can be attributed to hysteresis of the tyre rubber element [5].

Rubber has both viscous and elastic response to deformation. The viscous response is proportional to the rate of deformation while the elastic response is proportional to the amount of deformation [7]. Hysteresis is an inherent property of all visco-elastic material where the material relaxation takes more time than material compression time [6].

2.3.2. Impact of tire rolling resistance on vehicle fuel efficiency

This section investigates the contribution that rolling resistance has to vehicle fuel consumption, and discusses various methods that can be applied to predict the improvement in fuel economy that may be expected from reduced rolling resistance. A reduction in rolling resistance means that less torque needs to be provided to the wheels and the power needed to drive at the same speed therefore decreases. But inefficiencies in the vehicle engine and drive train result in a larger total energy expenditure than that transferred to the tires. Therefore, more fuel is saved than just the amount from a reduction in rolling resistance.

A tire's rolling resistance does affect the fuel economy. A 30% increase in RR increases fuel consumption by between 3% and 5% depending on driving conditions and vehicle type.

As we know, a vehicle's fuel economy is the result of its total resistance to movement. This includes overcoming inertia, driveline friction, road grades, tire rolling resistance and air drag. During stop-and-go city driving, the relative percent of influence from tire rolling resistance is about 15%, comparing with the steady speed highway driving of about 25% [9].

2.3.3. Simple analysis of the effect of rolling resistance on fuel consumption

We begin with some basic considerations of vehicle fuel consumption. While the analysis is too simplistic to represent a generic drive cycle with any vehicle accurately, the resulting relation captures the first-order effect of rolling resistance on fuel economy and provides some insight

into other relationships between them. A value of drivetrain efficiency can be used to describe the energy consumption for a specified drive cycle.

The total engine energy output may be expressed as

$$E_{Engine} = \frac{E_{tract}}{\varepsilon} + P_{acc} \times T \dots\dots\dots 2.1$$

Where E_{tract} the total tractive energy delivered over the drive cycle,

ε is the drivetrain efficiency,

P_{acc} is the average accessory power requirement, and

T is the total time of acc travel.

2.3.4. Rolling resistance coefficient on tyre

This linear approximation was thought to provide reasonable accuracy up to 80mph (129km/h). such equations were developed for use with table of rolling resistance coefficient appropriate for passenger car bias ply tire inflated to 32-40 psi (221-275 kpa). Various such table exist and they all depend on the tyre road surface considered and the level of technology (LOT) in effect at the time that the data was generated, so they all tend to be of limited application.

The phenomenon has both static (C_{sr}) and dynamic (C_{dr}), components as per an equation that was developed at the institute of technology in Stuttgart circa 1938.

This is perhaps the ultimate in rolling resistance modeling (or at least this author's favorite). Taborek present a plot of how "Csr" and "Cdr" vary with inflation pressure "Pi" that plot allows for a data "pick-off" and a subsequent regression analysis of the data.

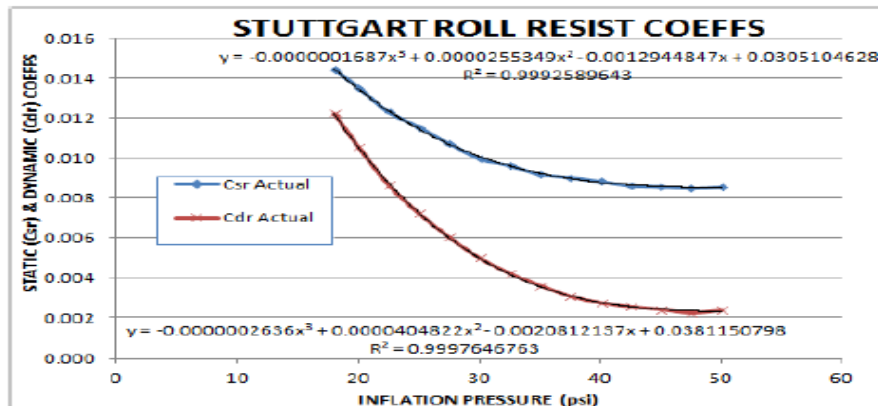


Figure 2.4: Rolling resistance coefficient VS inflation pressure

The regression analysis resulted in some very accurate expressions for “Csr” and “Cdr” as a function “Pi” for the 1938 LOT 6.00x16 reference tire. These expressions were used to establish the baseline reference “Csr” and “Cdr” values.

$$(C_{sr})_{Ref} = -0.0000001687P_i^3 + 0.0000255349P_i^2 - 0.0012944847P_i + 0.0305104628 \dots (2.2)$$

$$(C_{dr})_{Ref} = -0.0000002636P_i^3 + 0.0000404822P_i^2 - 0.0020812137P_i + 0.0381150798 \dots (2.3)$$

The “Csr” coefficient has to do mainly with the primary hysteresis/frictional aspect of rolling resistance and “Cdr” coefficient has to do mainly with the secondary aerodynamic aspect. [21]

2.3.5. Inflation Pressure and Load on the Rolling Friction Coefficient

The rolling friction coefficient μ_r decreases by increasing the inflation pressure p. The effect of increasing pressure is equivalent to decreasing normal load F_z . The following empirical equation has been suggested to show the effects of both pressure p and load F_z on the rolling friction coefficient.

The parameter μ_r is called the rolling friction coefficient. μ_r is not constant and mainly depends on tire speed, inflation pressure, sideslip and camber angles. It also depends on mechanical properties, speed, wear, temperature, load, size, driving and braking forces, and road condition.

$$\mu_r = \frac{K}{1000} \left(5.1 + \frac{5.5 \cdot 10^5 + 90 F_z}{p} + \frac{1100 + 0.0388 F_z}{p} V_x^2 \right) \dots 2.4$$

Where k is, the parameter K is equal to 0.8 for radial tires, and is equal to 1.0 for non-radial tyres.

The dissipated power because of total resistive force is equal to the total resistive force (means rolling resistance force, aerodynamic lifting force and gravitational force) times the forward velocity V_x . [17],

$$P_{used} = (\mu_r \times F_z + F_L) \times V_{bus} \dots 2.5$$

Where

P_{used} is brake power used (KW)

$$F_r = \mu_r \times F_z \text{ Rolling resistive force} \dots 2.6$$

F_L is total lifting force (kw) in each model

V_{bus} is the velocity of the bus (m/s)

Where P_{tyre} is the consumption per unit distance due to the tyres. We now consider the effect of a variation in rolling resistance for the drive cycle, and assume that the other loss terms do not change when rolling resistance is modified. Based on Eq. 2.5, the variation of the energy consumption per distance traveled be analyzed by Willans relation of power required to move and consumed power relation given by [23].

$$P_{consumed} = 2.23 \times P_{required} + 6.82 \times N_{rpm} \dots \dots \dots 2.7$$

The fuel consumption is now as a Willans relation of power consumed to the rated engine power

$$\dot{m} = \frac{P_{consumed}}{P_{rated}} \text{ it can be found as liter per km} \dots \dots \dots 2.8$$

The second equality in Equation vehicle assumes that the coefficient of rolling resistance for all tires on the vehicle is uniformly decreased by ΔC_R . Since the engine thermal efficiency η and drivetrain efficiency ε are both less than unity, this relation shows that a reduction in rolling resistance results in an amplified fuel energy savings. As mentioned above, the value of the thermal efficiency is rather Where $Q_{LHV} = 42.5 \text{ MJ/Kg}$ is lower heating value of diesel fuel and $\rho_{fuel} = 860 \text{ kg/m}^3$ is fuel density at the ambient temperature and η_{engine} is thermal efficiency of a diesel engine. [14].

The efficiency of an engine is defined as the ratio between the power required (brake power output) and the power consumed (fuel power consumption).

$$\eta = \frac{P_{required}}{P_{consumed}} \dots \dots \dots 2.9$$

2.4. Influence of temperature

The temperature of the tyre has significant effect on rolling resistance of tyre. Increasing of rolling resistance of tyre is due to the deflection and energy loss in the material.

This reduction of Rolling Resistance of tyre with temperature is caused by a combination of two actions; temperature sensitivity of hysteresis (i.e., hysteretic loss properties of most rubber compounds are temperature sensitive, being much higher at lower temperatures) and expansion

of air inside the tyre due to increase in tyre temperature. As the tyre temperature increases, the pressure inside the tyre also increases thereby reducing the deflection and in turn lowering the loss due to hysteresis [5].

2.5. Tread Wear

Friction between the tyre and the road surface causes the tread rubber to wear away over time. Government legal standards prescribe the minimum allowable tread depth for safe operation. There are several types of abnormal tread wear. Poor wheel alignment can cause excessive wear of the innermost or outermost rims. Gravel roads, rocky terrain, and other rough terrain will cause accelerated wear. Over inflation above the sidewall max can cause excessive wear to the center of the tread. However, inflating up to the sidewall limit will not cause excessive wear in the center of the tread. Modern tyres have steel belts built in to prevent this. Under inflation causes excessive wear to the outer ribs.

Unbalanced wheels can cause uneven tyre wear, as the rotation may not be perfectly circular. Tyre manufacturers and car companies have mutually established standards for tread wear testing that include measurement parameters for tread loss profile, lug count, and heel-toe wear.

When tyres wear, the volume of rubber in the tread reduces thereby reducing the hysteresis loss and in turn reducing the . Hence new tyres have slightly more Rolling Resistance than used tyres. A Rolling Resistance study carried out on two pairs of tyres, one pair fully worn while the other rarely used, it was seen that the worn-out tyre showed slightly lower equilibrium Rolling Resistance than the new tyre.

2.6. Influence of load

2.6.1. Tyre load carrying capacity at pressure (P)

TRA (Tire and Rim Association) was founded in 1903 to establish and promulgate interchangeability standards for tires, rims, valves and allied parts. These standards include tire loads and dimensions, and rim contour and valve dimensions. The formulae used to calculate tire loads are empirically based, are derived from information and field experience from member companies, and are fundamentally similar in format for all types of tires, except aircraft. In the interest of brevity, only the formula for calculating passenger car tire loads will be analyzed. The load limits calculated and shown in the TRA publications are considered maximum for the

pressure shown and, conversely, the pressures shown are considered minimum for the corresponding loads shown.

Higher pressures for high speed and other special circumstances are often recommended by vehicle and/or tire manufacturers and are acceptable as long as they do not exceed the maximum pressure marked on the passenger car tire. TRA and other standardizing bodies provide guidelines for adjusting the tire load/pressure relationship as a function of speed.

The intent of the formula from a standards perspective is to:

- Determine a load rating that allows a tire manufacturer to design and produce a tire that can perform satisfactorily to the tire manufacturer's individual design requirements and still be interchangeable with the same tire size produced by other manufacturers;
- Provide rational increments of load carrying capacities over the range of tire sizes of a given type and series.
- Take into account the requirements of the vehicle manufacturer and service conditions.

The first formula adopted by TRA was developed in the mid 1930's by C. G. Hoover, a mathematician who later served as the staff director of TRA. The formula was empirically derived, based on the effects of inflation pressure, tire section width (or section diameter as it was called for the early circular section tires) and rim diameter. It is thought that this formula was based on maintaining a uniform degree of deflection in the tires at their assigned loads and inflation pressures. The formula for what were called "Low Pressure" passenger car tires was [14],

$$L = 6.65P^{0.585}S^{1.702}[(D_R + S)/(19 + S)] \dots\dots\dots 2.10$$

Where:

L = tyre load carrying capacity at pressure P

P = tyre inflation pressure

S = tyre section width (on rim width = 62.5% of tire section width 1

D_R = nominal rim diameter

2.6.2. Tyre load/deflection and stiffness

Other researchers in the industry generally concur that the stiffness of pneumatic tires is controlled primarily by the inflation pressure and the tire dimensions, principally the tread width and outside diameter. The tire structure itself only accounts for about 10 to 15% of the tire's load carrying capacity at typical operating pressures.

First, one must look at typical load-deflection curves at various operational inflation pressures, as shown in Figure. The tire stiffness at a given pressure is derived from the slope (the tangent vertical stiffness) of the individual curves, which appear to be quite linear over normal ranges of operating load. As tires become lower in aspect ratio and develop a square footprint, the value of the tangent stiffness approaches that of the secant stiffness.

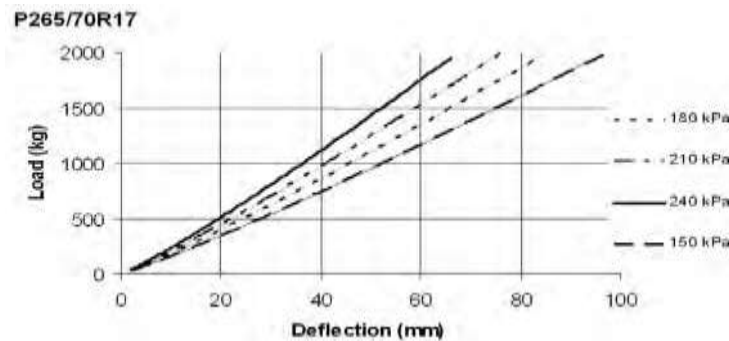


Figure 2.5: Load-deflection curves

For initial verification, the predicted K was calculated for 50 different tires of 34 sizes Z for which tangential stiffness had been measured at various loads and inflations pressures.

In order to make the stiffness equation more practical for use by standardizing bodies it is desirable to have the equation written in terms of parameters that these bodies normally deal with. First, a large sample of tires was evaluated to determine the relationship between footprint width and nominal section width [14].

Several interesting facts come to light when Rolling Resistance of a tyre is plotted against the vertical load at different temperatures. From Figure it is seen that there is significant reduction in Rolling Resistance of the tyres five minutes after the start of rolling, with very little reduction to its equilibrium temperature after the five minutes mark. A linear relationship develops between load and RR as the operating temperature increases.

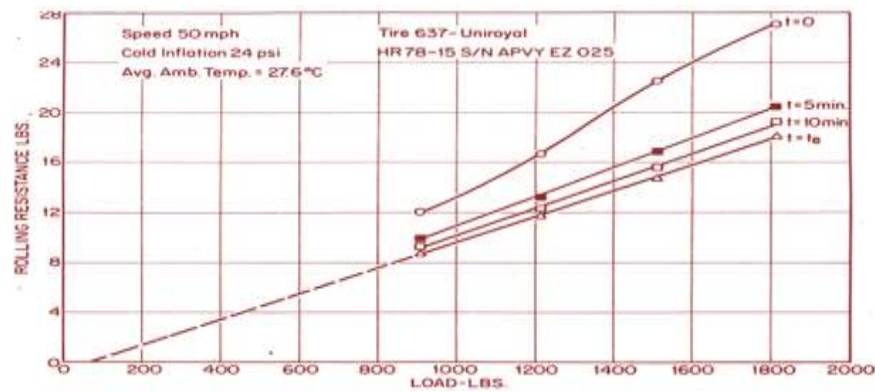


Figure 2.6 Rolling resistances versus vertical load

In the above Figure, a backward extension of the curve (at equilibrium temperature) nearly intersects the origin, implying that the Rolling Resistance is nearly zero at zero loads. This linear relationship of equilibrium Rolling Resistance versus load gives rise to the concept of coefficient of Rolling Resistance.

2.7. Contact Patch (Footprint) Phenomena

As can easily be seen, improper tire pressure can significantly impact fuel economy, tire mileage, and casing retread ability. It is also primarily responsible for tire-related, enroute breakdowns which are a significant cost to line haul fleets in not only tire and road service charges but also in lost driver and vehicle productivity (as the average road service down time is 2.5 hours). Improper inflation pressure also changes the tire contact patch which affects stopping and acceleration traction and vehicle handling thereby impacting vehicle safety. Properly maintained and performing tires aid drivers in preventing and mitigating crash situations.

Despite the Department of Transportation (DOT) requirement that commercial drivers conduct pre-trip inspections of their vehicles including the tires on them, tyre inflation pressures are still not well maintained. There are many reasons for this:

- It takes too long to check tyre pressure with a gauge (20 minutes on an 18-wheeler),
- checking pressure is a dirty job,
- the inside dual is difficult to reach and may be impossible to check if the valve stem is not properly aligned with the hand hole of the outside dual wheel [15].

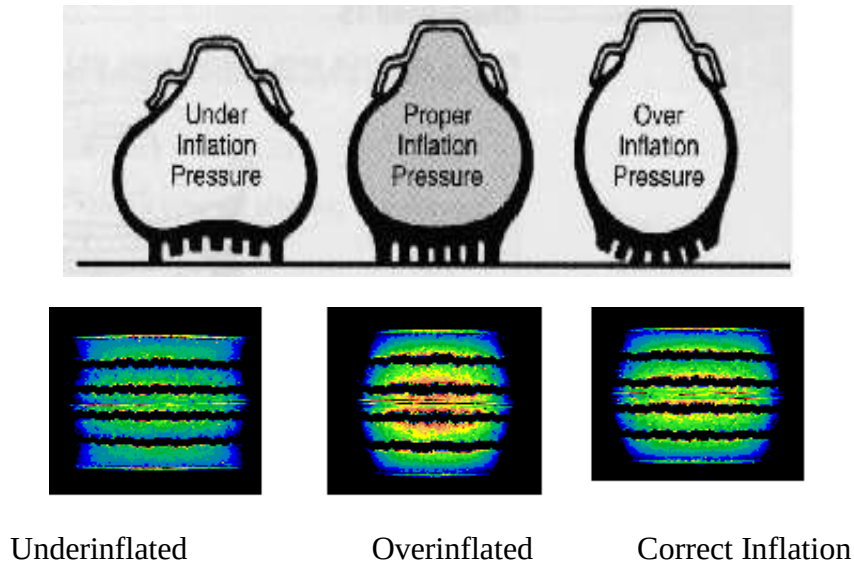


Figure 2.7: Tire Footprint and Inflation Pressure

Some parameters that might require evaluation could diameter (rim rolling) width (rim, tire) number of plies, type of material (carcass, rubber) tire volume, tire surface area. This approach begins the formula for the tread contact area “Ac” of a tire under load.

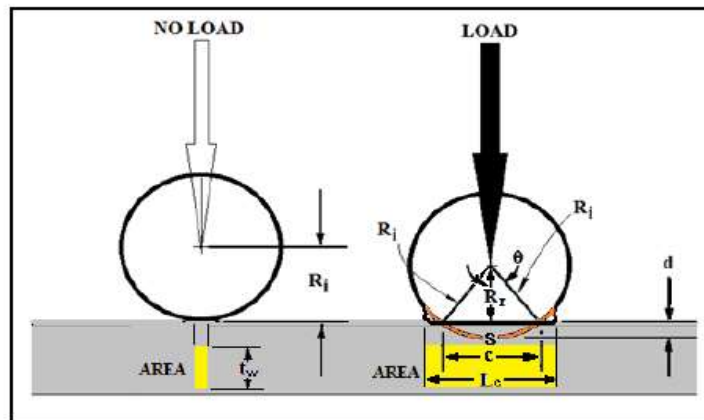


Figure 2.8: Tire contact area under load

$$A_c = L_c \times t_w = 1.24 R_i \cos^{-1} \left[\frac{(R_i - d)}{R_i} \right] t_w \dots \dots \dots 2.11$$

Use of this equation requires knowledge of the tread width “ t_w ” and deflection “ d ” under load “ N ”. The tread width may be determined by the “Michelin Formula” [21].

$$t_w = 0.03937(-0.0044R + 1.03)S_N \dots \dots \dots 2.12$$

2.8. Influence of tyre pressure

Proper inflation pressure is necessary for optimum tire performance, safety, and fuel economy. Correct inflation is especially significant to the endurance and performance of radial tires because it may not be possible to find 5psi $\approx$ 35 kPa under-inflation in a radial tyre just by looking.

However, under-inflation of 5psi $\approx$ 35 kPa can reduce up to 25% of the tire performance and life.

It has been observed from data on several tyres that the RR varies nearly linearly with the reciprocal of tyre inflation pressure under steady-state conditions (i.e. constant load and speed).

According to the Rubber Manufacturer's Association, when a tyre is under inflated by 1 lb, the tyre's rolling resistance is increased by approximately 1% and that a 5–8% deterioration in rolling resistance performance, which equates to a roughly 1% reduction in fuel efficiency [Calwell et al., 2003]. This is similar to the review study done by Schuring and Futamura [1990] that found for each 10% reduction in the rolling resistance coefficient the fuel efficiency increased by 1.2–2.5% for city and 0.9–2.1% for highway driving. This is because inflation pressure determines tyre stiffness, which has a significant influence on the contact area of the tyre and pressure distribution over the contact surface. Thus, as pressure in the vehicle's tyres is reduced, the rolling resistance increases over the road because the surface contact area and virtual hill height is increased. When the rolling resistance is increased, it takes more energy (fuel) to get the automobile to go the same distance [5].

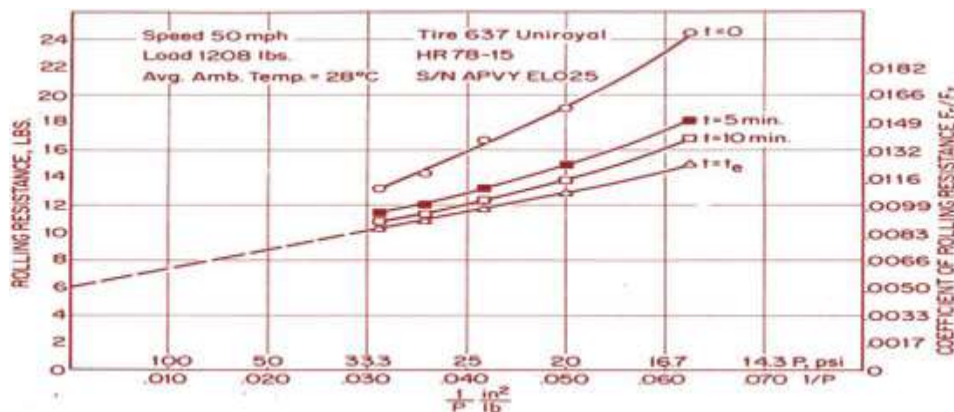


Figure 2.9 rolling resistance versus increasing inflation pressure

Inflation pressure

Increasing inflation pressure stiffens the tyre structure. The cornering stiffness will peak with increasing inflation pressure and then fall off as the pressure is increased further.

Increasing inflation reduces the size of the footprint, and thus the amount of tread rubber in contact with the road. At some point, the reduction in cornering stiffness due to a lower area of contact outweighs the increase in carcass stiffness due to increased pressure and the cornering stiffness begins to fall. A reduction of aligning torque is associated with an increase in inflation pressure because the shorter footprint also reduces pneumatic trail.

Additionally, increasing unit loading on the tread rubber reduces friction as shown by Ervin and associates. Thus, if the inflation pressure is adequate to prevent buckling under the expected lateral and longitudinal forces, increasing the inflation pressure will likely lead to lower apparent friction [16].

2.9. Factors Affecting the handling Performance of a Vehicle

Aerodynamics is one of the leading factors in vehicle performance. Car racing has focused on this aspect early in the 1960's, when the first invented wings were installed on formula cars. In time, the development of aerodynamic devices grew stronger, often borrowing ideas and solutions from the flight industry. By improving aerodynamics, engineers saw faster lap times and more driver control over the car, both at high and low speeds. The final element that contributes to improved handling and grip is the down force - using the underbody of the vehicle to facilitate airflow and "stick" the car to the tarmac [Johnson, 2005].

Another factor that affects vehicle performance is tyre pressure. Simply put, failure to maintain right tyre pressure on a consistent basis may result in faster tyre wear, tyre failures and loss of control, thus resulting in possible serious injuries or even property damages. More importantly, having the correct tyre pressures mean that the vehicle will be in better control, lesser chances of experiencing tyre blowouts or punctures and therefore preserving precious life [5].

2.9.1. Influence of tyre pressure on vehicle handling performance

The overall stiffness of a tyre and its weight bearing capability is primarily decided by the air inside the tyre. Thus, the tyre inflation pressure can considerably affect the overall vehicle performance. This is clearly evident in racing applications where extreme care is taken to

maintain appropriate air pressure in all the tyres since a trained driver is able to sense even the slightest variation in pressure, especially when driving at the limit. Thus, it is useful, and maybe even essential to capture the effects of tyre pressure in a tyre model for design and simulation purposes.

Traditionally, the lateral tyre characteristics were measured at fixed speeds and inflation pressures. This approach demanded a large number of tests and measurements to enable the study of tyre forces and moment characteristics across all operating parameters. Many of the tyre models developed over the years have either ignored the effects of tyre pressure in them or could not sufficiently validate the results obtained from it. The influence of tyre pressure on the three main handling parameters of tyres namely, longitudinal force, lateral force and aligning moment, will be examined in the sections below [6].

2.9.2. Tyre forces and moments

Tyre forces and moments are complex non-linear functions of the tyre usage variables that are established by driver inputs and vehicle responses. On a laboratory test machine or an over-the-road testing device, the test conditions are established by the need to explore the expected range of usage. To allow communication, modeling, and use of the resultant data, a formal language has been developed for describing inputs to the tyre and the force and moment responses developed by the tyre.

There are two axis system developed this are, SAE Tire Axis System and the ISO Wheel Axis System have their origins at the road since the source of tire forces and moments is at the road surface. In the following, the first mention of a term defined within a terminology document is capitalized to identify the fact that it is a universally defined term.

2.9.2.1. The SAE tire axis system

The figure below portrays the SAE Tire Axis System [5, 6]. The system is a right-handed, three-axis, orthogonal, Cartesian coordinate system with its origin at the Contact Center in the road plane. The road plane is the plane tangent to the road surface at the contact center. The contact center is the point in the road plane where the line defined by the intersection of the Wheel Plane (the plane halfway between the rim flanges) to road plane is cut by the projection of the Spin Axis onto the road plane. Thus, the contact center is defined by the wheel, not the tire. It is

defined in terms of the wheel because the tire is flexible and the exact location of its center of contact at any given moment is indeterminate. The SAE X' axis is along the line defined by intersection of the wheel plane with the road plane, the contact line. Positive X' is in the intended rolling direction for the tire. The SAE Y' -axis is along the projection of the spin axis onto the road plane. Positive Y' is to the right when the system is viewed from the rear looking in the positive X' direction. The SAE Z' -axis is defined by the cross product of $+X'$ into $+Y'$. It is perpendicular to the road plane with its positive sense into the road plane [16].

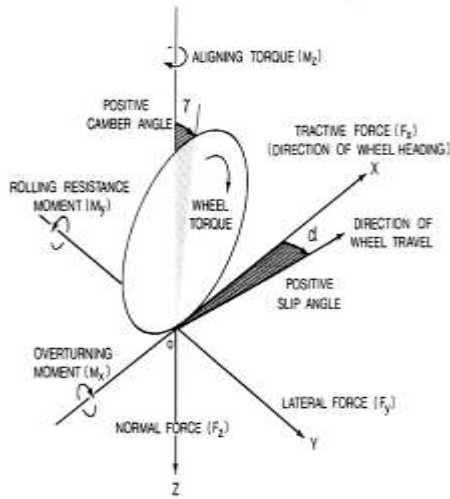
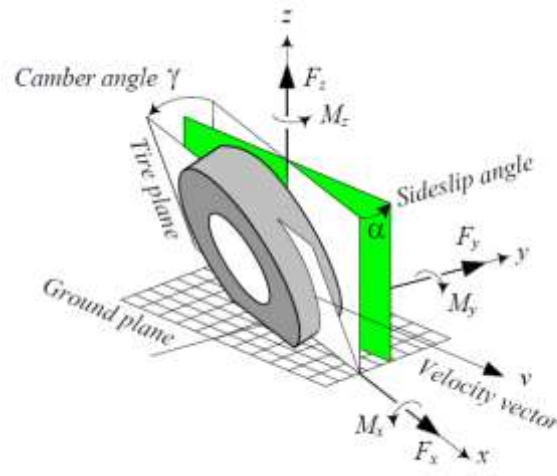


Figure 2.10: a. Tire axis system



b. Tire coordinate system.

Since the precise effective location at which the road applies forces to the tire is unknown and the origin of the tire axis system is arbitrarily defined by the wheel and road geometry, three forces (F_X , F_Y , and F_Z) and three moments (M_X , M_Y , and M_Z) are required to define the road's action upon the tire [17].

Each of the three forces acts along its associated axis in the tire coordinate system. For example, F_X acts along X' .³ The positive direction for each force is the same as the positive direction for its associated axis as indicated in figure 1. The three forces are defined as follows.

Longitudinal force, F_X , is the force of the road on the tire along the X' -axis. It accelerates or decelerates the vehicle dependent on whether the tire is driven or braked. If F_X is positive, the tire is driven, and F_X is called driving force. If F_X is negative, the tire is braked, and F_X is called braking force.

Lateral Force, F_Y , is the force of the road on the tire along the Y' -axis. It forces the vehicle to move to the left or right dependent on whether the tire is steered and/or cambered to the left or right.

Normal force, F_Z , is the force of the road on the tire along the Z' -axis. It is the contact force between the road and tire. By definition, it is negative.

Each of the three moments acts about its associated axis in the tire axis system. For example, M_X acts about X' . The right hand rule applies. The positive sense for each moment is clockwise about the positive branch of its associated axis when looking away from the tire axis system origin along the positive branch of the axis. This is shown in figure 1. The three moments are defined as follows.

Overturning moment, M_X , is the moment about the X' -axis. It accounts for the effect of left-to-right displacement of the point of action of the normal force with respect to the contact center. M_X influences camber behavior.

Rolling resistance moment, M_Y , is the moment about the Y' -axis. It accounts for the fore-aft displacement of the point of action of normal force with respect to the contact center. M_Y is somewhat misnamed, as it has little to do with rolling resistance.

Aligning moment, M_Z , is the moment about the Z' -axis. It accounts for the point of action of the shear forces, F_X and F_Y , within the road plane.

2.9.3. Lateral force

Several authors [14, 15] have concluded that the lateral stability of a vehicle is largely governed by the tyre's cornering stiffness coefficient, C_α , which determines the lateral force characteristics of a tyre [6].

In this section, the influence of tyre pressure on the tyre force and moment characteristics will be presented to investigate the Anbessa city bus handling performance.

Cornering stiffness is mathematically defined as follows, i.e. the slope of the lateral force versus slip angle at zero slip angle.

$$F_y = F_{y0} + jF_y = -C_\alpha \alpha$$

$$C_{\alpha} = \lim_{\alpha \rightarrow 0} \frac{\partial F_y}{\partial \alpha} \dots\dots\dots 2.13$$

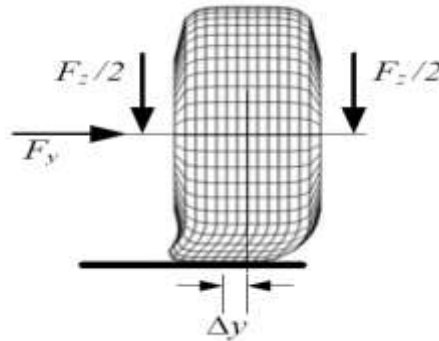


Figure 2.11: Front view of a laterally deflected tire.

Two clear trends emerge when studying the effect of air pressure on cornering stiffness. Higher inflation pressure results in lower cornering stiffness at lower vertical loads on the tyre. This is clearly visible from Figure, which shows a typical relationship between inflation pressure and load, for a passenger car tyre. This behavior can be explained by realizing that the tyres overall stiffness increases with increase in air pressure thereby reducing the tyre deformation and in turn its contact patch length.

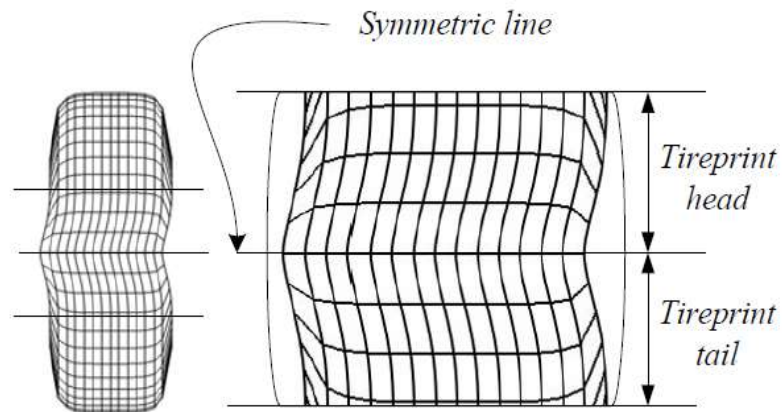


Figure 2.12: a... Laterally deflected tire b. Tire print

If the laterally deflected tire is turning forward on the road, the tire print will also flex longitudinally. A bottom view of the tire print for such a laterally deflected and turning tire is shown in Figure below. Although the tire-plane remains perpendicular to the road, the path of the wheel makes an angle α with tire-plane. As the wheel turns forward, un-deflected treads enter the tire print region and deflect laterally as well as longitudinally.

The cornering stiffness C_α of radial tires are higher than C_α for non-radial tires. This is because radial tires need a smaller slip angle α to produce the same amount of lateral force F_y .

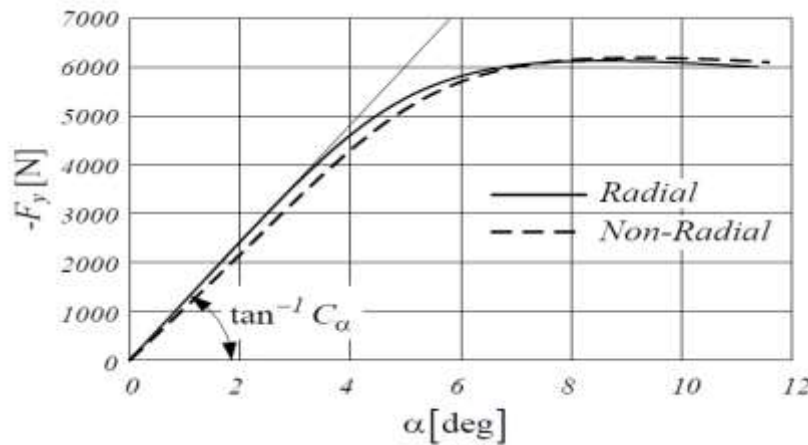


Figure 2.13 Lateral force F_y as a function of slip angle α for a constant vertical load.

2.10. Aerodynamic analysis of a rotating wheel of a vehicle

Nowadays, when car companies are trying to reduce fuel consumption and lower CO_2 emission, aerodynamic design of cars and its components plays important role. According to different sources even up to 25% of the car aerodynamic drag comes from wheels [1, 2]. Car manufacturing companies and tyre manufacturers are facing problems connected with reduction of friction coefficient as well as improving air flow around the tyre and whole car body.

The importance of vortices located near the area of contact between the tyre and the ground was highlighted by [4]. As a result, the flow phenomena described by e.g. [4,5,6,7], among others, shed light at the importance of analyzing vehicle aerodynamics with inclusion of rotating wheels, both experimentally and numerically, a practice that before 1990s was quite seldom. However, still a number of publications strictly connected with investigation of tyre geometry using Computational Fluid Dynamics (CFD) in synergy with experiment is limited. For example, very recently [8, 9] observed that there is a difference in aerodynamic drag depending on whether a vehicle is equipped with slick or grooved tyres. Namely, the aerodynamic drag is lower for an automobile with grooved tyre (a production sedan and a model of compact car were tested). This claim shifts analysis of tread pattern influence on vehicle aerodynamics back to isolated wheel study in order to search for explanation of this phenomenon [20].

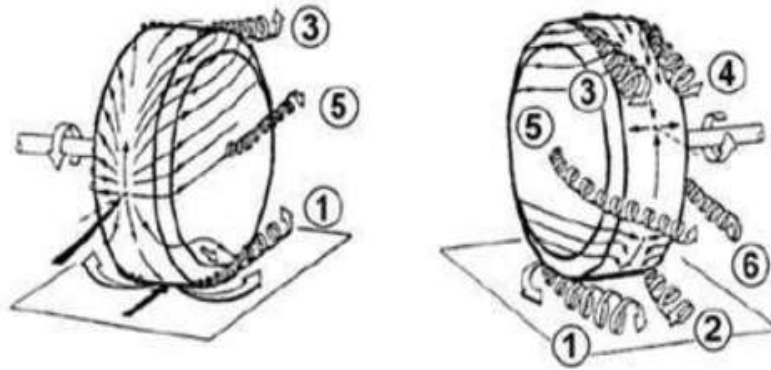


Figure 2.14 Aerodynamic characters on vehicle rotating wheel

2.10.1. Aerodynamic drag of the rotating tyre

Rotating objects disturb the air around them. This movement of air—or drag resists the object's rotation. The bigger the object (i.e. the greater the surface area in contact with the air), the greater the resistance. Resistance also increases with the square of the speed of rotation (just as a vehicle's aerodynamic drag increases with the square of its speed). The aerodynamic drag of a rotating tyre accounts for between 0 and 15 % of rolling resistance [22].



Figure 2.15: Aerodynamic drag of the rotating tyre

2.10.2. Aerodynamic performance analysis of rotating tyre

For the analysis of a rotating tyre in a different tyre inflation pressure the aerodynamic performance seen with the lifting force and drag (C_l) by the static pressure distribution on the

surface of vehicle was analyzed. The lifting force and drag coefficient were calculated from the equation given below.

- Lifting force (F_L) and the coefficient (C_L)

$$\sum F_L = \frac{1}{2} C_L \rho_{air} \sum A_{tyre} V_{bus}^2 \dots\dots\dots 2.14$$

CHAPTER THREE

METHODOLOGY

In this chapter it is described how the research is conducted and the sampling technique used to analyses the influence of tyre inflation pressure on the fuel consumption and vehicle handling performance and also presents the methodology and tools and software used to build models of tyre.

A survey of vehicles was conducted in Anbessa city bus. The survey was based on field data on vehicles in Addis Abeba. The survey was based on field data on bus by considering its tyre inflation pressure range and fuel consumption on road.

Three vehicle tyre models are built in different range of inflation pressure using CATIA. The aerodynamic drag of rotating tyre was analyzed using on PHOENCIS VR 215 software. The effect of tire inflation pressure on fuel consumption and handling performance were analyzed.

After the tyre pressure data were collected and the tyre models were built. The average deviation of inflation pressure from the recommended was calculated. The effect of inflation pressure on rolling resistance was found by analysis of tyre models

The static stress analysis of tyre models with different inflation pressure was done on ANSYS 15.0 software.

3.1. Geometry

Because tyres have to carry heavy loads, steel and fabric cords are used in their construction to reinforce the rubber compound and provide strength. The most common materials suitable for the tyre application are cotton, rayon, polyester, steel, fiberglass, and aramid.

There are two major ingredients in a rubber compound: the rubber and the filler. They are combined in such a way to achieve different objectives. The objective may be performance optimization, traction maximization, or better rolling resistance. The most common fillers are different types of carbon black and silica.

Tyres are combined with several components and cooked with a heat treatment. The components must be formed, combined, assembled, and cured together. Tyre quality depends on the ability to blend all of the separate components into a cohesive product that satisfies the driver's needs. A

modern tyre is a mixture of steel, fabric, and rubber. Generally speaking, the weight percentage of the components of a tyre is:

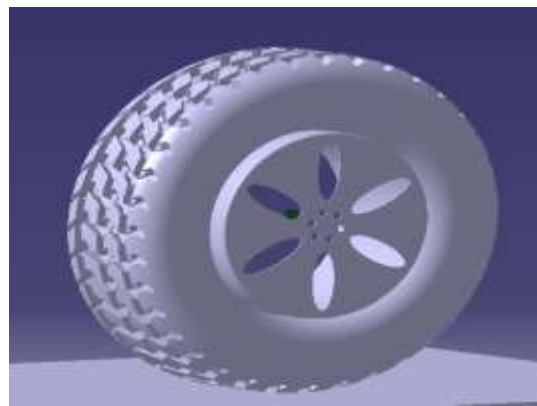
- Reinforcements: steel, rayon, nylon, 16%
- Rubber: natural/synthetic, 38%
- Compounds: carbon, silica, chalk, 30%
- Softener: oil, resin, 10%
- Vulcanization: sulfur, zinc oxide, 4%
- Miscellaneous, 2%

Material properties: Rubber

Density = 2.33 Kg/m^3

Young's modulus = 50000 N/mm^2

Poisson's ratio = 0.49



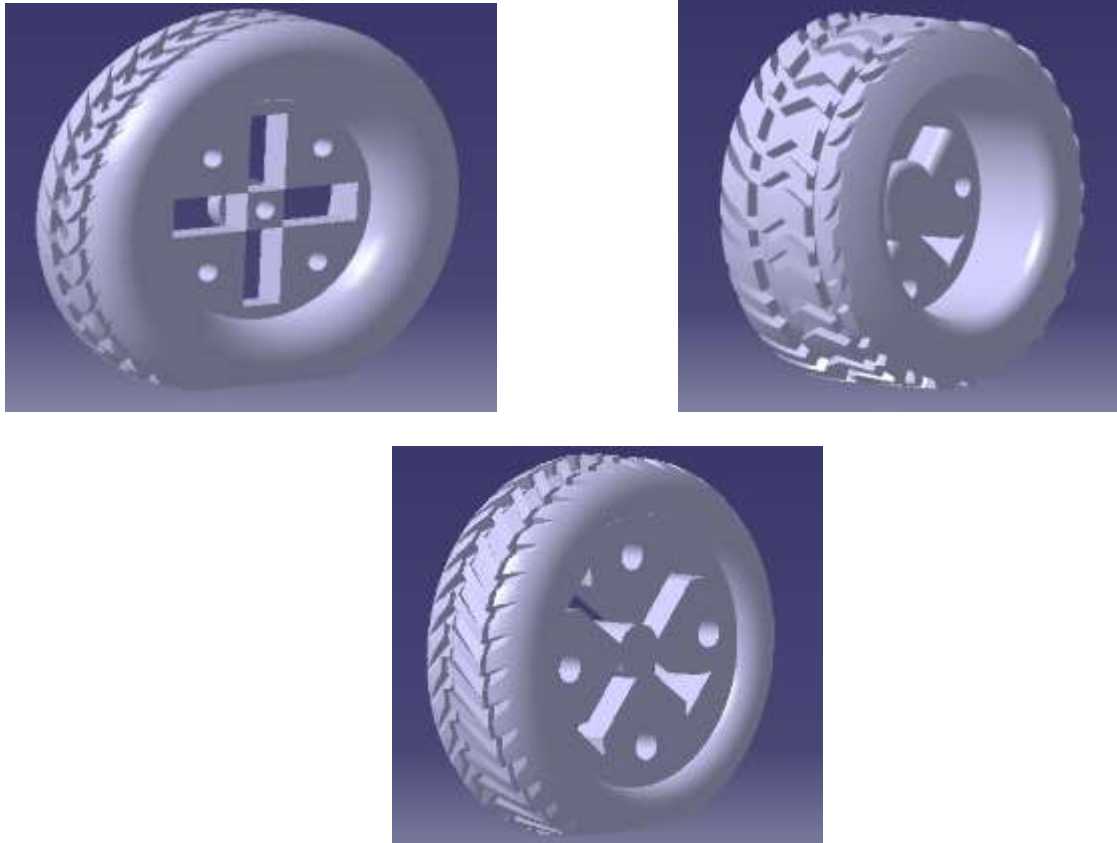


Figure 3.1 CATIA Models existing tyres

3.1.1. Model Descriptions and Assumptions

Theoretically, a tyre model should consider the following:

- All tyres used were from the same manufacturer; HORIZEN ADDIS TYRE MANUFACTURING
- A 295/80R22.5 size number tyre was maintained throughout the experimentation;
- Tyre widths were matched as closely as possible; however not all tyres were available in the same width hence there was some slight variation;
- The composite structure (rubber and reinforcement) and the significant anisotropy caused by great differences in stiffness between rubber and reinforcement;
- The large deformation due to flexibility of tire carcass during contact with the pavement surface;
- The rim was modeled as a rigid body and in contact with the bead at the end of sidewall.
- The near-incompressibility and the nonlinearity of rubber material.

The tyre models commonly used for tyre design purposes must accurately predict the deformation of the whole tyre and the interaction of internal pressure force during forward motion connecting with rolling resistance as well. Because this study is also can see the tyre deformation as it relates to the contact region because of improper tyre inflation pressure and the resulting fuel consumption and vehicle handling performance contact stress distributions at the tyre-pavement interface.

3.2. Operating range

Initial Boundary conditions

- Velocity condition of Anbessa city bus is up to 120km/hr.
- The bus cover 150km on half day (12hr)
- On a dry surface.
- No slip condition at the surface of the model tyre
- Moving boundary condition on the ground surface of road.

Three tyre model geometries were analyzed. Tyre model geometry was created based on the tyres used mostly on Anbessa city bus in Addis Abeba its tread structure, inflation pressure and overall dimension is from HORIZON ADDIS TYRE manufacturing. But in the analysis the load carrying capacity of the tyre is equally used in each model. The models are different size number. The tyre models are created by CATIA V5R20.

Table 3.1 The model of tyres in different inflation pressure.

Model no	Specification
Model 1 A 295/80R22.5 size number	At normal inflation or recommended
Model 2 A 295/80R22.5 size number	High inflation condition
Model 3 A 295/80R22.5 size number	Under inflation condition

Model 1

- P295/80R22.5 size number
- At normal inflation or recommended 0.83MPa
- Maximum load-carrying capacity tire 7100kg the load index is 152/148.
- Maximum speed is 65km/hr – 120km/hr tire index is D,E,F,G,J

Model 2

- P295/80R22.5 size number
- High inflation condition 0.90MPa
- Maximum load-carrying capacity tire 7100kg the load index is 152/148
- Maximum speed is 65km/hr – 120km/hr tire index is D,E,F,G,J

Model 3

- P295/80R22.5 size number
- At Under inflation condition 0.7MPa
- Maximum load-carrying capacity tire 7100kg the load index is 152/148.
- Maximum speed is 65km/hr – 120km/hr tire index is D,E,F,G,J

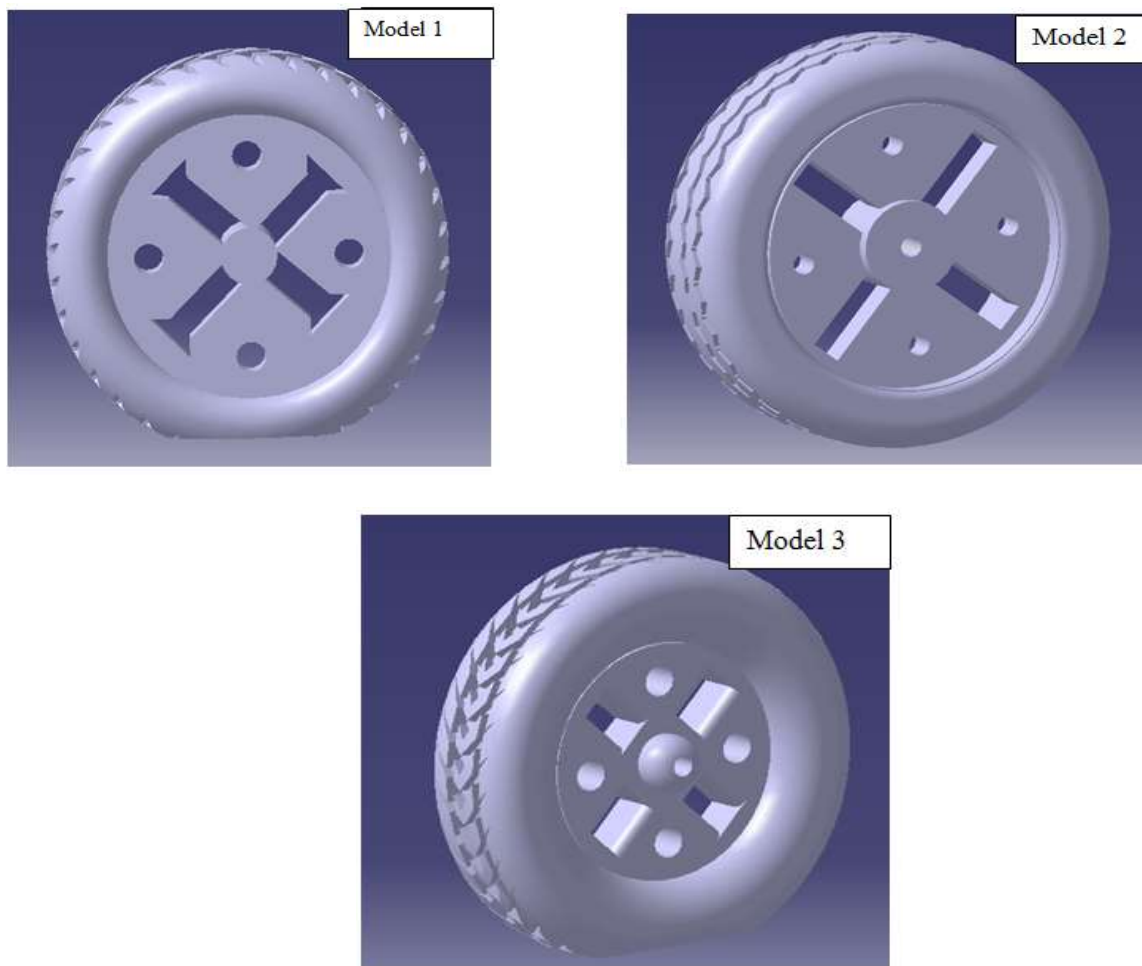


Figure 3.2 CATIA Models of tyres.

Vehicle Model: Anbessa city bus

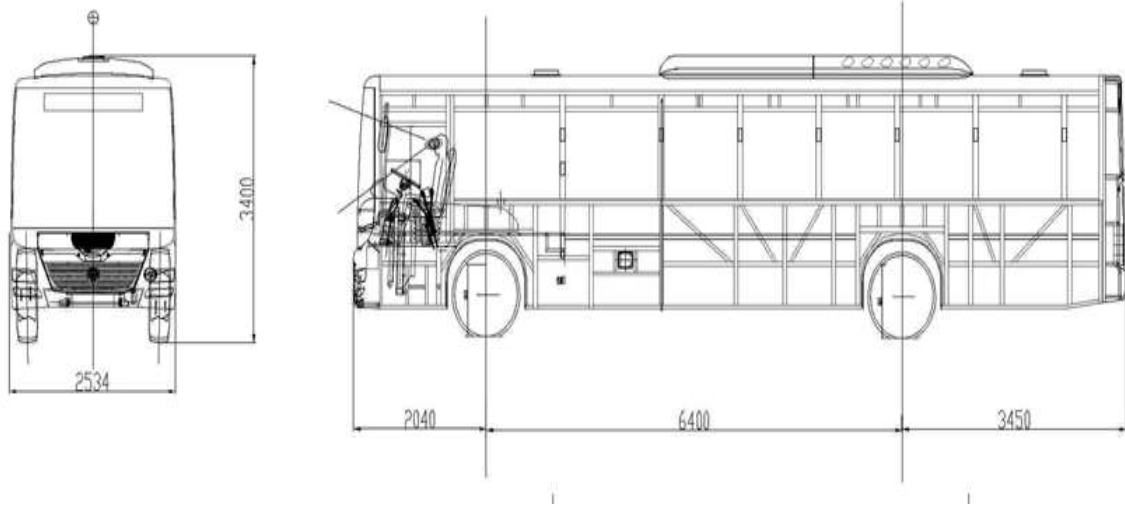


Figure 3.3 Vehicle Model: Anbessa city bus

Table 3.2 Technical specification of the bus

Engine capacity		9726ml	
Number of cylinder(z)		Six	
Arrangement of cylinder		Inline arrangement of cylinder	
Types of engine		Diesel engine	
Types of ignition system		Spark ignition	
Types of cooling system		Water cooling	
Maximum brake power(P_{b-max})		199kW/1900rpm	
Maximum brake Torque (T_{b-max})		1270Nm/1200-1500rpm	
Vehicle Dimension		Weight Distribution and Others	
L	11890mm	Quality parameters(kg)	kg
W	2550mm	Curb weight	11300
H	3400mm	Front axle	5700
Wheel base	6400mm	Rear axle	5600
X1	58.45cm	Gross weight	18500
G, Clearance	210-231mm		
Front track (mm)	1880mm		
Rear track(mm)	3380mm		

3.3. Measurement of tyre pressure and fuel consumption on Addis Abeba city bus

The tyre inflation pressure was measured when the tyres of Anbessa city bus were inflated in tyre inflation room in workshop. The bus registration number is 8179 selected for data measurement. Three dimensional model of the tyre was prepared using dimensions obtained from manufacturing.

If the tyre pressure is below or above the recommended tyre pressure, more fuel may be consumed. This means that more fuel will be needed for the same amount of distance to be covered. The fuel consumption analysis of tyre in a different range of inflation pressure is done by relating the rolling resistance phenomena on each tire models.

From the field data collected from the bus is in following table. From the data gathered from the bus which is 8179 side number we can analyses the Average tyre pressures and the corresponding fuel consumptions for in a given kilometer. In each day, the selected bus tyre pressures, odometer reading and the fuel reading were recorded for each analysis. Records were taken at intervals of 11 hour.

Table 3.3: Reading of tyre pressure, taken kilometer and fuel consumed

	Odometer reading(km)	Fuel consumed (litter)	Tyre pressure measured (MPa)			
			Front right	Front left	Rear right avg	Rear left avg
Day 1 2:30 PM	18004	40	0.812	0.806	0.751	0.749
11: 30 PM	18122	6.1733 left				
Day 2 2: 30 pm	18973	40	0.825	0.829	0.801	0.793
11: 30 pm	19096	3.1 left				
Day 3 2: 30 pm	19941	40	0.791	0.819	0.761	0.795
11:30 pm	20063	4.01 left				
Day 4 2: 30 pm	20903	40	0.783	0.791	0.810	0.788
11:30	21031	3.3 left				
Day 5 2:30 pm	21872	40	0.831	0.810	0.792	0.81
11:30 pm	21995	2.485 left				
Day 6 2:30 pm	23205	40	0.71	0.73	0.751	0.76
11:30 pm	23326	-0.33 left				
Day 7 2:30 pm	24168	40	0.76	0.771	0.71	0.708
11:30 pm	24290	0.35 left				

From the average pressure was found and the fuel consumption in kilometer, that is, the fuel was divided by the distance covered and the results were presented in Table below.

Table 3.4: Average fuel consumption at different average tyre pressure

Average tyre pressure (Mpa)	Fuel consumed (litter/km)
0.78	0.287
0.813	0.299
0.8	0.293
0.79	0.286
0.86	0.34
0.71	0.333
0.73	0.325

Table 3.5 Measured tyre pressure of Anbessa city bus

	Front right (Mpa)	Front left (Mpa)	Average front (Mpa)	Rear right (Mpa)	Rear left (Mpa)	Average rare (Mpa)
Day 1	0.812	0.806	0.809	0.751	0.749	0.75
Day 2	0.825	0.829	0.827	0.801	0.793	0.797
Day 3	0.791	0.819	0.805	0.761	0.795	0.778
Day 4	0.783	0.791	0.787	0.811	0.788	0.7995
Day 5	0.831	0.81	0.82	0.792	0.81	0.801
Day 6	0.71	0.73	0.72	0.751	0.76	0.755
Day 7	0.76	0.77	0.765	0.71	0.708	0.70

From the data gathered from Anbessa city bus for different tyre pressure fuel consumption can be calculated by finding rolling resistance for each pressure range. The fuel consumption was calculated at particular weight of the vehicle and speed covering the same distance, by using the rolling resistance values at different tyre inflation pressure. The aerodynamic drag on each tyre model was found from CFD analysis.

3.4. Tyre rolling resistance coefficient on each tyre model

The rolling coefficient (static and dynamic coefficient) of tyre based on a different tyre inflation pressure and on the same surface or road condition, with the same vehicle forward speed is calculated using equ (2.2) and equ (2.3). Also at the same vehicle speed and same distance traveled.

$$(C_{sr})_{Ref} = -0.0000001687P_i^3 + 0.0000255349P_i^2 - 0.0012944847P_i + 0.0305104628$$

$$(C_{dr})_{Ref} = -0.0000002636P_i^3 + 0.0000404822P_i^2 - 0.0020812137P_i + 0.0381150798$$

Now we can also see the rolling friction coefficient variation on each tyre models developed because of varying inflation pressure and surface contact developed on road by relating the scientific characteristic of the rolling coefficient μ_r decreases by increasing the inflation pressure p . The effect of increasing pressure is equivalent to decreasing normal load F_z .

$$\mu_r = \frac{K}{1000} \left(5.1 + \frac{5.5 * 10^5 + 90F_z}{p} + \frac{1100 + 0.0388F_z}{p} V_x^2 \right)$$

By equation (2.4) is used to show the effects of both pressure p and load F_z on the rolling coefficient of the Anbessa city bus.

Power dissipated in the bus

Knowing the vehicle's characteristics and tyre rolling resistance coefficient, we can calculate the value of each resistive force and total resistive force for each model of tyre at different inflation pressure, using equation (2.6) and aerodynamic lifting force from CFD using equation (2.13).

Rolling resistive force can also lead to more fuel consumption the variation of the energy consumption per distance traveled based on a change in tire rolling resistance is given by.

$$F_r = \mu_r F_z$$

Where μ_r is rolling friction coefficient of each tyre models.

Lifting force developed in each tyre model because of rotation of tyre is

$$\sum F_L = \frac{1}{2} C_L \rho_{air} \sum A_{ty print} V_{bus}^2$$

Then we look at each resistive force in turn. For each model of tyre we calculate the power required and corresponding consumption at each inflation pressure.

The dissipated power because of rolling friction and lifting force developed in tyres is equal to the summation rolling resistive force F_r and lifting force developed times the forward velocity v_x . Using Equation (2.5), the power dissipated is

$$P_{used} = \mu_r (F_z + F_L) * V_{bus}$$

3.5. Procedure: For CFD phoenics VR simulation

Arrange domain of the experiment simulation for finding rotational drag on the tyre.

- Size of the controlled region is X= 30m, Y= 4.6m, Z= 5m.
- By boundary conditions of the domain using inlet, outlet and ground plate
- Importing tyre model size at scale of 1:100 reducing and the dimensions are diameter of 1044mm and width is 298mm
- Set initial condition wind velocity is $V=60\text{km/h}$
- Set the position of sensor in the domain at X= 2.1m , Y= 0.5m , Z= 0.07m as shown
- Calculate drag coefficient from total forces at the reference density of 860kg/m^3 , reference area in x,y and z of tyre print in each model.
- The current domain material treated at air at 1atm
- For solution of pressure and velocity distribution
- Using question formulation ELLIPTIC STAGGERED
- Total number of iteration is 1000
- Global convergence criterion is 0.01
- Tolerance is 0.001

New Object: creates a new object and displays the object dialog for the newly-created object. It is equivalent to clicking on „Object – New – New Object“ on the Object Management Dialog reached from the button on the hand-set or the O icon on the toolbar.

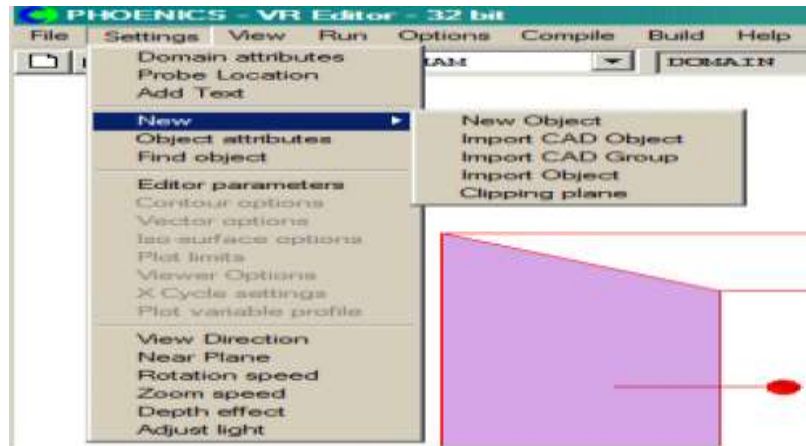


Figure 3.4 CFD phonice working page

Import CAD Object: tyre model created by CATIA is to imported



Figure 3.5 CFD part selection and adjustment window

Settings - Object Attributes

This brings up the object dialog box for the currently-selected object. It is equivalent to double-clicking on an object. If no object is already selected, the Object Management Dialog showing a list of all objects will be displayed.

Settings - Find Object

This brings up the Object Management Dialog. The selected object (if any) becomes the current object, and is high-lighted in the list of objects.

Settings - Editor Parameters

The VR Editor Parameters menu sets the Increment size, and Scale factors.

By adjusting all working specification and run for simulation to analyze the rotational drag coefficient and lifting force developed on each tyre model.

Run - Pre processor

The Preprocessor sub-menu contains the following items

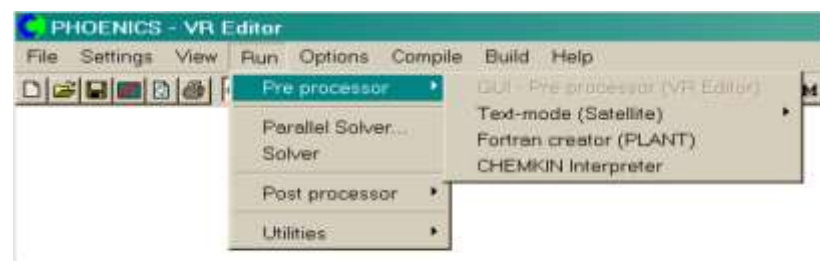


Figure 3.6 CFD run the process view

3.5.1. Aerodynamic drag coefficient and lift force analysis of each tyre model by CFD phoenics VR simulation for each model of tyre pressure

Aerodynamic performance analysis of tyre in a different range of inflation pressure condition

The drag coefficient (C_L) and lifting force was from CFD.

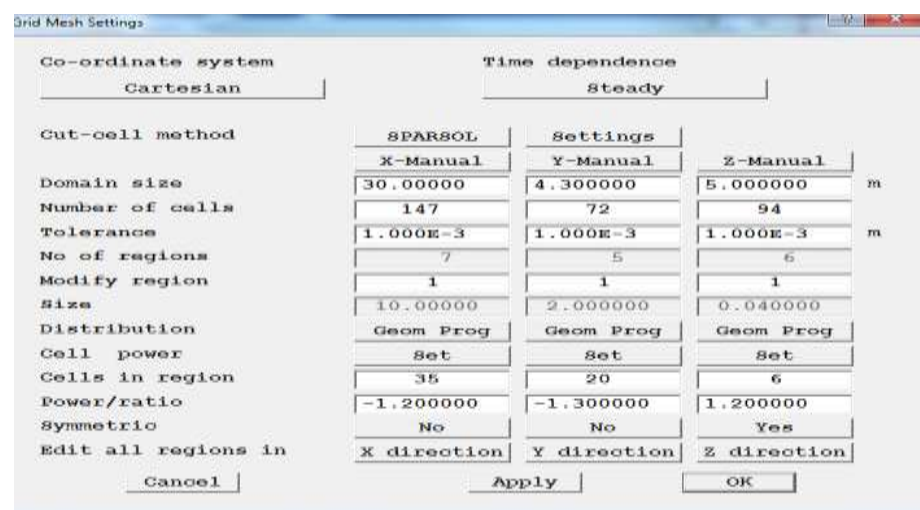


Figure 3.7 CFD mesh adjustment way

Model 1 Recommended

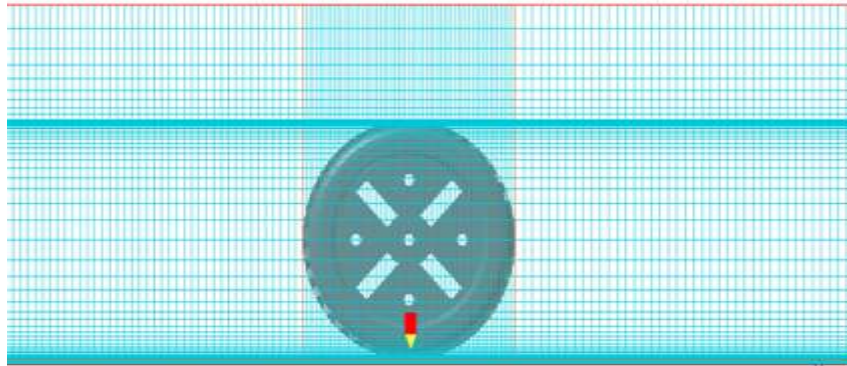


Figure 3.8 CFD mesh of model 1

Model 2 Under inflation

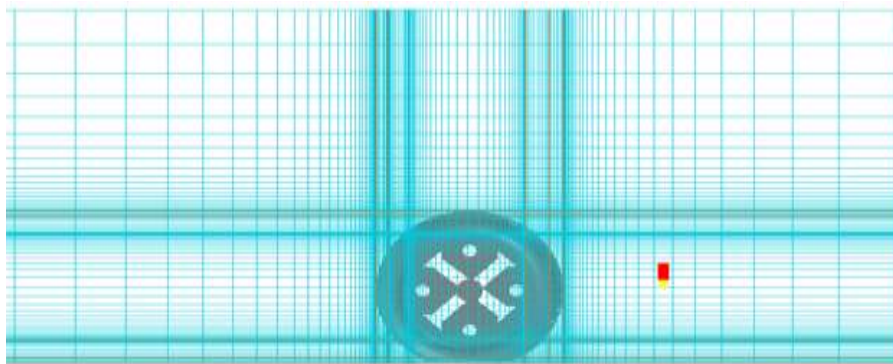


Figure 3.9 CFD mesh of model 2

Model 3 Over inflation

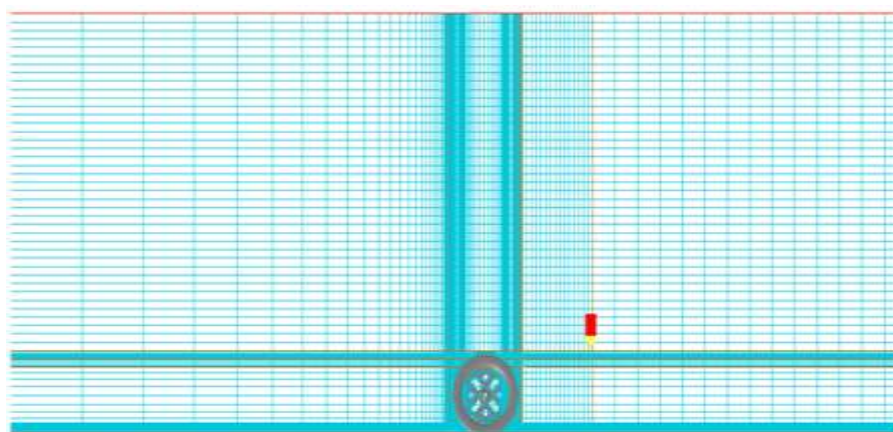


Figure 3.10 CFD phoenics VR meshed tyre model 3

After the CFD simulation we get Lifting force (F_L) and the coefficient (C_L) force developed because of rotational aerodynamic effect in a different range of tyre inflation pressure using the equation (2.13)

3.6. The Tyres inflation pressure contribution on fuel consumption in each model

Finally the amount of fuel consumption can be calculated on each tyres model due to overall effect of tyres rolling resistance and the rotational aerodynamic drag of tyre in a different range of inflation pressure, on the same vehicle load, speed and same level road.

Fuel used by this model calculated by Willans relation of power required and power consumed to analyze the amount of fuel consumption in a given 60km/hr. the moving.

$$P_{consumed} = 2.23 \times P_{required} + 6.82 \times N_{rpm}$$

And the rated power of the engine rotation. For this bus the rated power 199Kw per liter.

$$\dot{m} = \frac{P_{consumed}}{P_{rated}} \text{ is to be found liter per kilometer.}$$

3.7. Vehicle handling performance

When evaluating the stability of a vehicle, the lateral forces and longitudinal force generated because of the bus tyre inflation pressure variation must be taken into consideration. The specification of a Anbessa city bus sized vehicle, same for all tyre models used and the analysis of contact surface of the tyre configured on the same road.

The analysis of vehicles during cornering behavior can be tested on the Steady-state cornering. In steady state cornering approach, the inertial effects of the vehicle in motion is neglected as the vehicle speed is constant.

The tyres develop a slip angle and are oriented perpendicular to the turn radius as shown by a simple bi-cycle model. The contact surface of the tyre configured on the lateral and longitudinal tyre stiffness are important point of the aerodynamic performance of car in different inflation range.

In order to do a comparative study of the influence of changing tyre pressure on the bus in three cases of studies to investigate the results of longitudinal and lateral force developed.

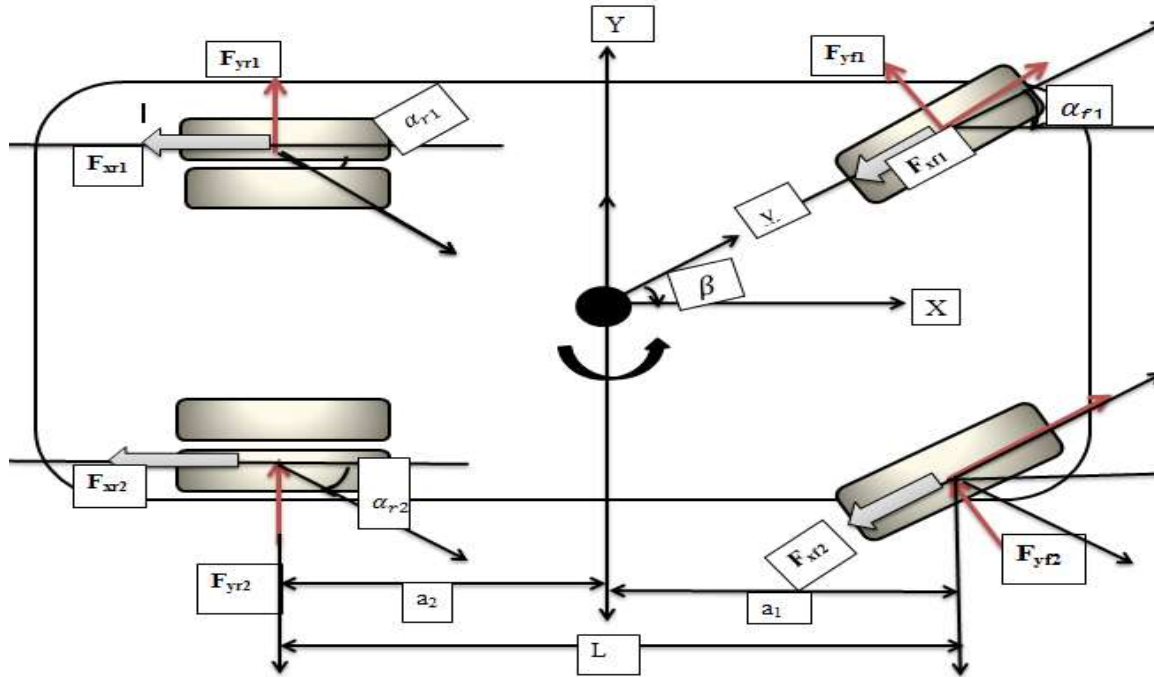


Figure 3.11 Cornering of the bus

Tyre model handling performance analysis can be done by ANSYS. The full tyre model was prepared using geometrical and material properties. In this study, the tyre model was created by the CATIA V5R20 software and with each tyre pressure models. Then, this model is imported to ANSYS and the appropriate studies of longitudinal and lateral forces have been displayed. The tyre interaction with the road was simulated in ANSYS version 15.0 by three critical consideration of the tyre when the bus steers at low speed utilize to the lateral and longitudinal force in each tyre pressure models.

- The tyre model was loaded with uniform tyre inflation pressure at its inner surface in each model.
- The 3-D tyre models were generated and placed in contact with pavement under the applied load.
- Finally, each tyre model was rolled on pavement with same angular (spinning) velocities and transport velocities.

In this study, the pavement (road) was modeled as a non-deformable flat surface (asphalt). This assumption is considered reasonable because the tyre deformation is much greater than the pavement deflection when wheel load is applied on the tyre and transmitted to the pavement.

surface. The large deformation of the tyre was taken into account by using a large-displacement formulation in ANSYS. Type of meshing used is tetrahedral.

This analysis utilizes the static analysis and can consider the effect of tyre inflation pressure and the tyre pavement reaction force interface. The analysis is done on each tyre model by applying the loads of bus weight and person's weight.

The ANSYS simulation is done by applying appropriate physical and mechanical properties of tyre in each model.

Table 3.6 Simulated material properties

	Physical property	Mechanical property
Tyre in each model	Hyper elastic material ➤ neoprene rubber	Incompressibility parameter
Rim	Density ➤ 7850 kg/m ³	Tensile yield strength ➤ 2.5×10^8 pa Tensile ultimate strength ➤ 4.6×10^8 pa
Pavement (asphalt road)	Density 2300 kg/m ³ Young's modulus 30 pa Poisons ratio 0.18	

The descriptions of these Cases are given below:

Model I: recommended tyre pressure of 8.3 bar (0.83MPa) in front tyres.

Model II: over inflation pressure of 9 bar (0.90MPa) in front tyres.

Model III: under inflation pressure of 7.0 bar (0.7MPa) in front tyres.

3.8. Tyre Pavement Contact Stresses

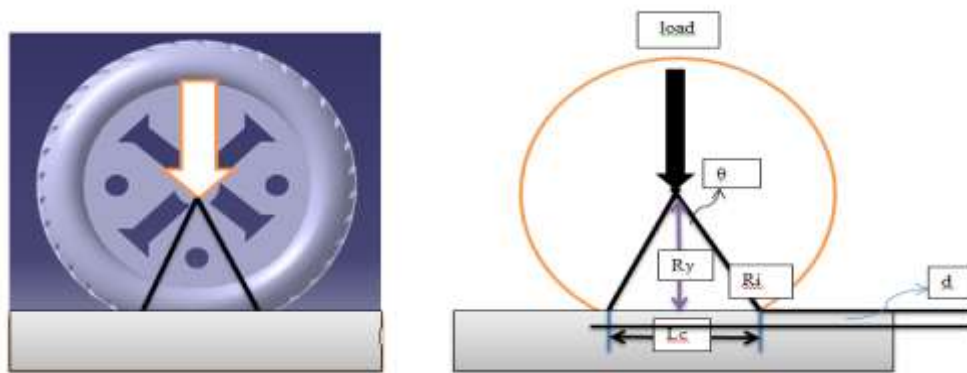
Because the focus of this study is the effect of inflation pressure in fuel consumption and handling performance also we have seen what was the tyre print occurred because the total load of vehicle and different inflation pressure. It shows the maximum stress occurred area and deformation created in tyre when the same applied force, (Fz) loaded on the tyre when the bus at the static condition with different tyre pressure. The analysis includes the following

- Apply a vertical load, which represents the weight of a vehicle means Ambessa bus.
- Perform a static full 3D footprint analysis of the tyre in contact with a flat road.

The tyre carrying capacity can be analyzed by using the tyre size number by standard formula generated by Tyre and Rim Association (TRA). Equation (2.7) was empirically derived, based on the effects of inflation pressure, tire section width (or section diameter as it was called for the early circular section tires) and rim diameter.

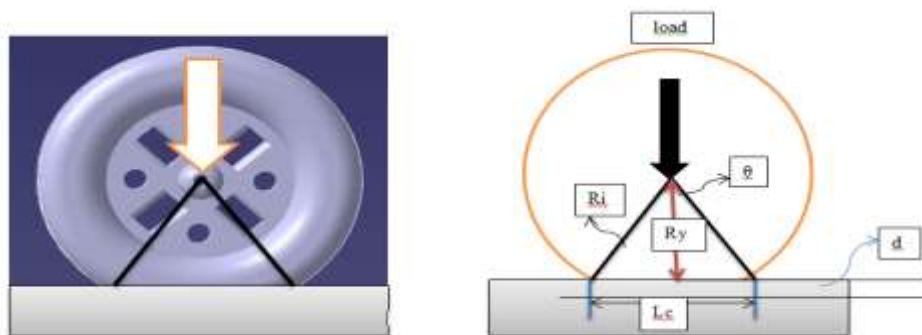
This study that shows the contact stress and deflection of tyre can be simulated on ANSYS 15.0 static structure software.

Model 1 Manufacturer recommended



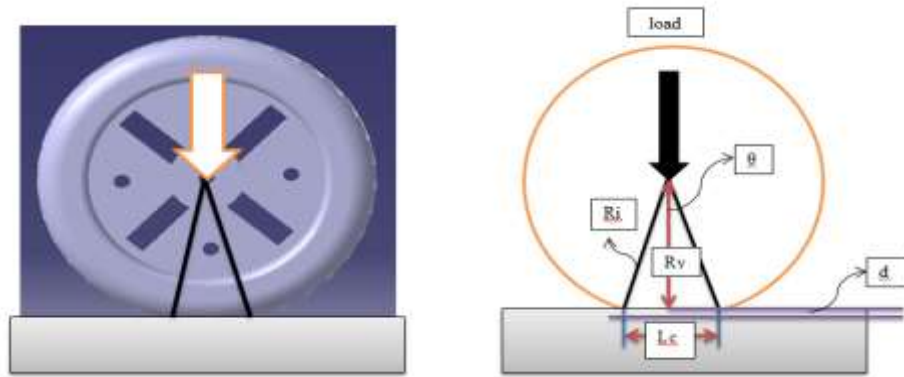
a. Tyre stress concentration analysis model 1

Model 3 Under inflation



b. Tyre stress concentration analysis model 3

Model 2 over inflation



C. Tyre stress concentration analysis model 2

Figure 3.12 Tyre stress analysis models

Because of the identical vertical load ($F_z = 46,250$ N) of the bus on the tyre for different pressure the tyre stress concentration will be different.

CHAPTER FOUR

RESULTS AND DISCUSSION

This chapter looks at the quantitative analysis result of the study. This section presents all the results obtained from the mathematical calculation and simulation of the three tyre models of recommended pressure, over and under inflation range. Using these results, the influence of inflation pressure on the fuel consumption and handling performance are discussed.

4.1. Tyre rolling resistance coefficient on each tyre model

A field survey was conducted on the Anbessa city bus to find out the inflation pressure of the tyre. Tyre pressure gauge was used to measure the tyre pressures of the vehicles.

For each tyre inflation pressure tyre rolling resistance coefficient was calculated. Figure 4.1 shows the variation of tyre rolling resistance coefficient at different tyre inflation pressure of Anbessa city bus.

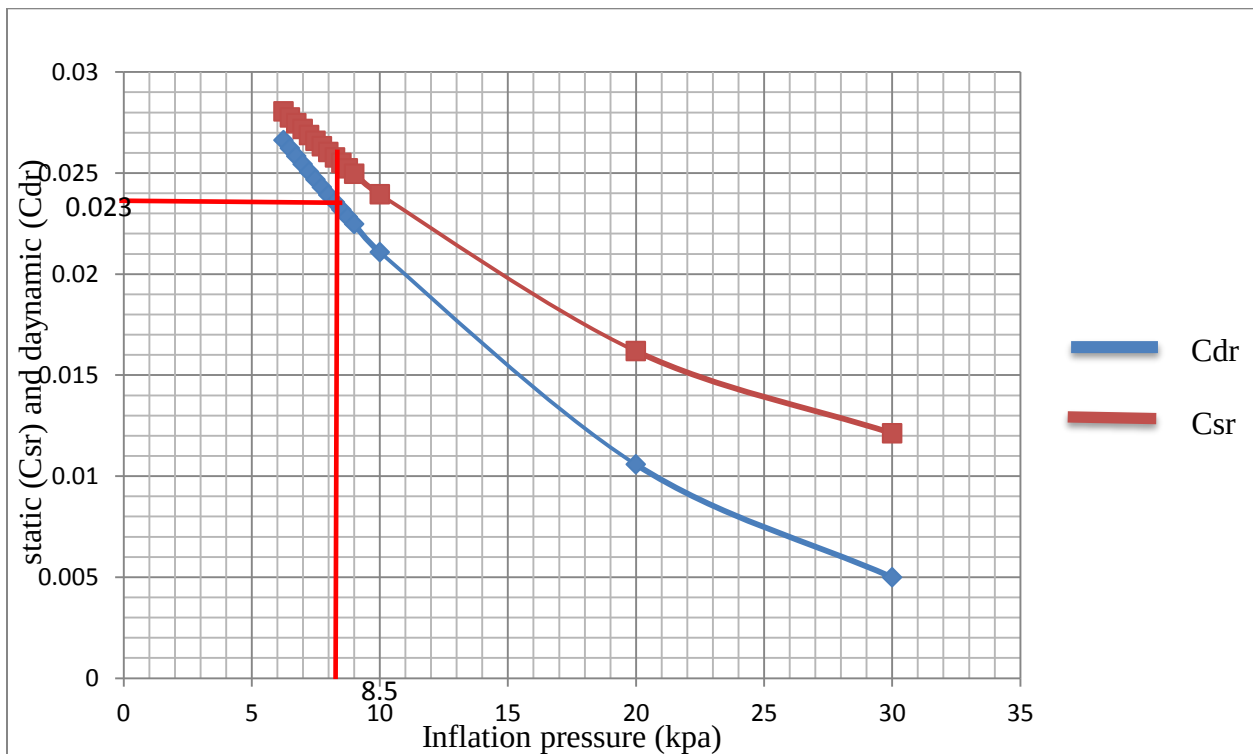


Figure 4.1 Tyre static and dynamic coefficients versus inflation pressure

Table 4.1 Static and dynamic rolling coefficient in each model

Tyre models	Pressure in (Mpa)	Static rolling coefficient Csr	Dynamic rolling coefficient Cdr
Model 3	0.7	0.027	0.025
	0.75	0.027	0.025
	0.775	0.026	0.024
Model 1	0.83	0.026	0.024
Model 2	0.85	0.026	0.023
	0.875	0.025	0.023
	0.9	0.025	0.022

In the above Table 4.1, the tyre rolling resistance coefficient on each tyre models with different inflation pressure (model 1 is 0.83MPa, model 2 is 0.90MPa and model 3 is 0.70MPa). The curb weight of vehicle is assumed to be equally distributed among the four tyres. It can be seen that the estimated static and dynamic tyre rolling resistance coefficient decreased while increasing the tyre inflation pressure and vice versa. In model 2 (over inflation pressure) the dynamic coefficient of tyre decreases, this decrease leads in to higher breaking distance and over steering effects. As the tyre inflation pressure increase the surface contact will decrease, so the dynamic rolling resistance decreases. The static rolling coefficient is higher on the under inflation pressure than the over inflation pressure because there is an increase in the surface area. In model 3 (under inflation pressure) the static coefficient becomes higher as compared to model 1 and 2; it indicates that high initial force is needed during steering and starting.

It is observed that the static and dynamic rolling coefficient varies on each model with varying inflation pressure. With recommended tyre inflation pressure the static coefficient is (0.026) and the dynamic coefficient is (0.024). Most of the Anbessa city bus tyre pressures being (10 – 19.99) % less than the recommended tyre pressure, that static and dynamic coefficients occur (0.026-0.027) and (0.024-0.025).

4.2. Effect of Inflation Pressure and Load on the Rolling Friction Coefficient

Rolling friction coefficient was calculated by considering the load of the bus at different tyre inflation pressure. The calculation was done for all three models with a load of $F_z = 46,250\text{N}$ and forward speed of 60 km/hr. Variation of tyre rolling friction resistance of Anbessa city bus with vehicle speed for all three models is shown in fig. 4.2. The data is given in table 4.2.

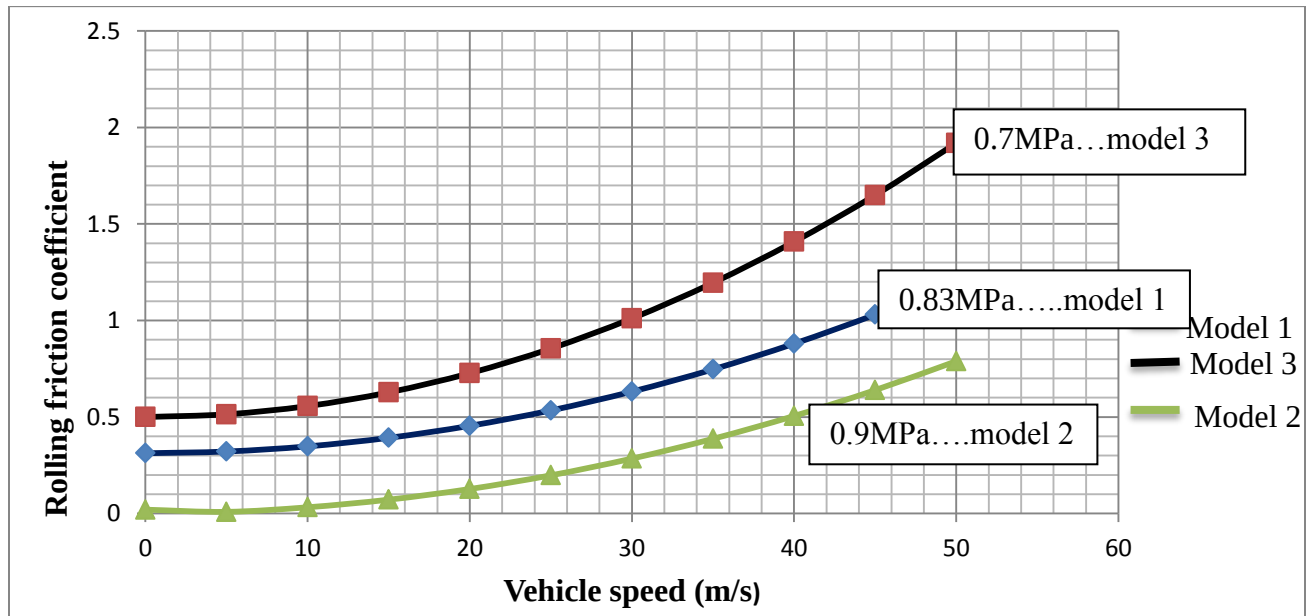


Figure 4.2 Rolling friction coefficient Vs. vehicle speed

Table 4.2 Rolling friction coefficient with speed in each tyre model

Speed (m/s)	Rolling friction coefficient		
	Model 1	Model 2	Model 3
5	0.36	0.01	0.51
10	0.38	0.02	0.56
15	0.4	0.04	0.63
16.67	0.44	0.07	0.73
25	0.48	0.11	0.85
30	0.54	0.16	1.01
35	0.6	0.22	1.2
40	0.67	0.28	1.41

For the models the rolling friction coefficient had reduced as the tyre inflation pressure increased, it can be seen that the rolling friction coefficient in model 3 which is shown in the graph had increased by 24.8% as compared to model 1 with in the same vehicle speed and load. Also, for the model 2 (over inflation) the rolling friction coefficient reversely decreased by 72.5% from model 1. According to sources [4, 19] and others, a 10 % reduction in rolling friction coefficient can bring about 2 % reductions in the fuel consumption. Whether this 2 % estimation was made at fixed values of speed, vertical load and pressure is not clearly specified in the references, though it wouldn't be surprising if it were so.

Hence, the rolling friction resistance increases it also increasing as the contact surface increase. As a model 2 has high pressure tyre the contact surface area is low, lower rolling resistance than the model 3 and model 1 a low pressure tyre on asphalt road.

4.3. Aerodynamic analysis of rotating tyre

Before finding the overall contribution of tyre inflation pressure on the fuel consumption we can see the result of aerodynamic effect of rotating tyre in each model on drag coefficient and the lift force (F_z).

Model 1

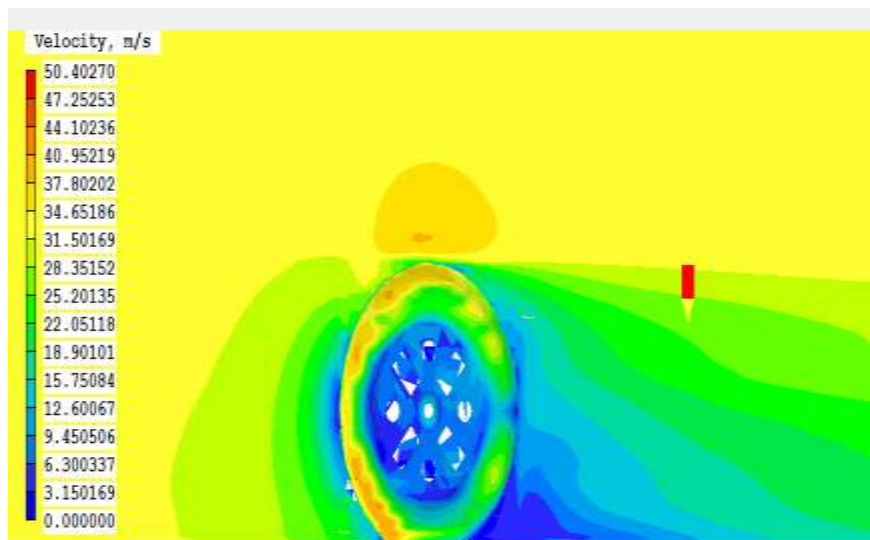


Fig 4.3 a. Velocity variation on model 1

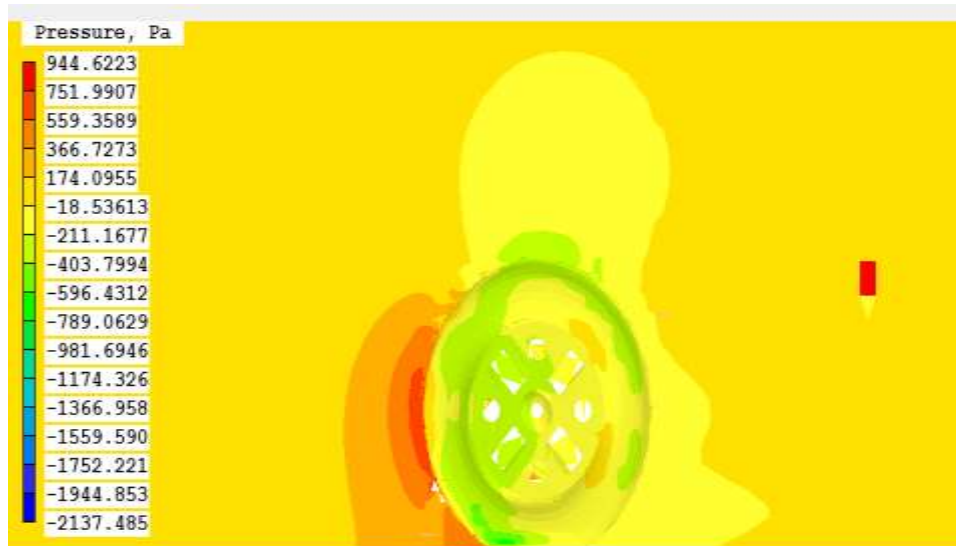


Figure 4.3 b. pressure variation on model 1

Integrated forces for all included objects

$$F_x = 2.819055E+01$$

$$F_y = -9.997255E-01$$

$$F_z = 7.573506E+00$$

$$F_{tot} = 2.920727E+01$$

Model 2

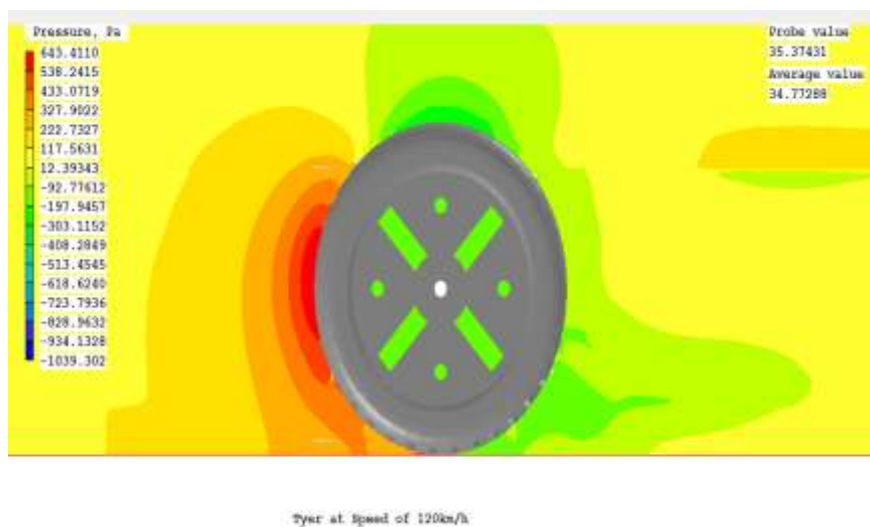
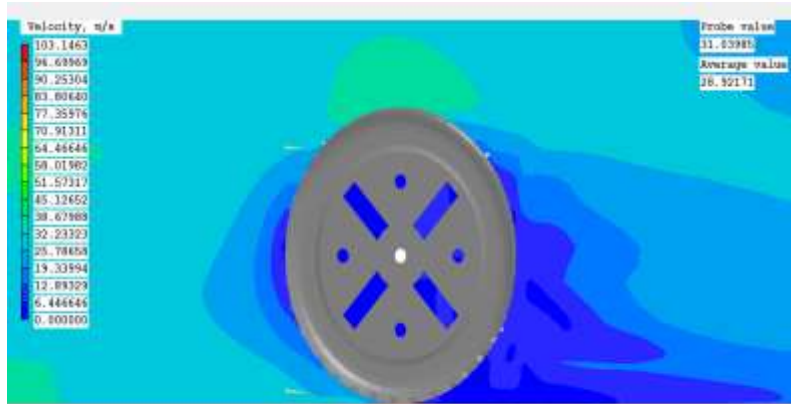


Fig 4.3 c. Pressure variation on model 2



Tyre at Speed of 120km/h

Figure 4.3 d. Velocity variations on model 2

Integrated forces for all included objects

$$F_x = 2.405660E+01$$

$$F_y = -3.114434E-01$$

$$F_z = 6.479037E+00$$

$$F_{tot} = 2.491576E+01$$

Drag coefficients based on total forces:

$$(C_d = \text{Force} / (\text{Dynamic head} * \text{Normalisation area}))$$

$$C_{dx} = 4.046527E+01$$

$$C_{dy} = 5.238745E-01$$

$$C_{dz} = 1.089830E+01$$

Model 3

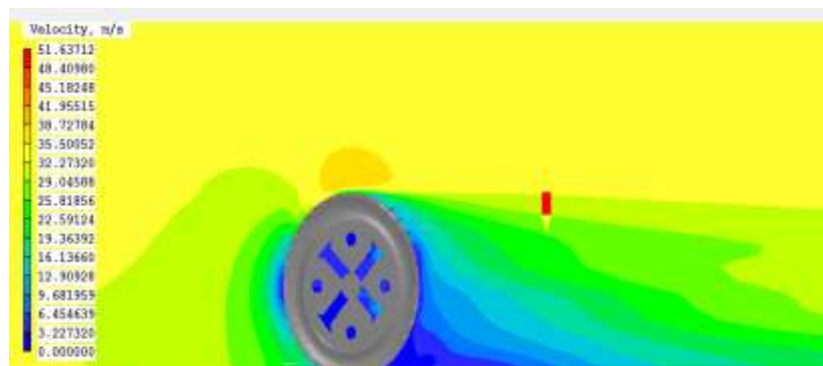


Fig 4.3 e. Pressure variation on model 3

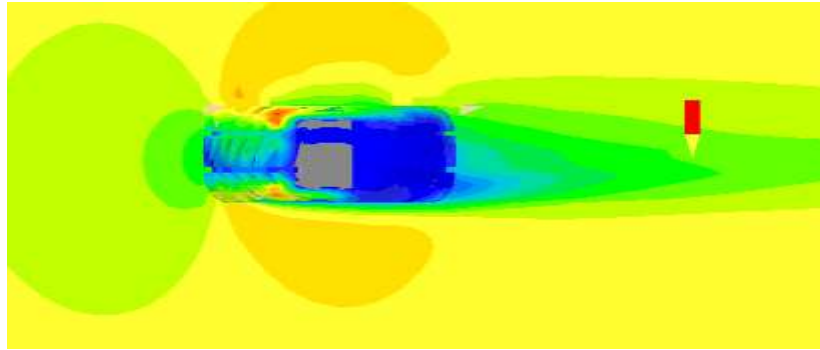


Figure 4.3 f. Velocity variations on model 3

Integrated forces for all included objects

$F_x = 3.311916E+01$

$F_y = -2.014180E+00$

$F_z = -3.342777E-01$

$F_{tot} = 3.318203E+01$

Drag coefficients based on total forces:

$(C_d = \text{Force} / (\text{Dynamic head} * \text{Normalisation area}))$

$C_{dx} = 5.570927E-01$

$C_{dy} = 3.388024E+00$

$C_{dz} = 5.622838E-01$

Table 4.3 Aerodynamic simulation result (lifting and C_d) of rotating tyre in each model

Tyre model	Integrated tyre force and drag at speed 120 km/hr	
	Lifting Force developed	C_d
Model 1	$F_z = 7.573506E+00$	$C_{dx} = 4.056928E-01$
Model 2	$F_z = 6.479037E+00$	$C_{dx} = 4.046527E+01$
Model 3	$F_z = -3.342777E-01$	$C_{dx} = 5.570927E-01$

As indicated in the literature review the aerodynamic lifting and drag are developed on the vehicle is 25% factor is tyre rotation, now lifting force and drag coefficient at a different speed and at a different tyre inflation pressure the aerodynamic performance can be seen in following table.

Table: 4.4 The lifting force and drag coefficient with in a different speed

		Lifting force and Cd at different speed		
		60km/hr	80km/hr	120km/hr
Model 1	Rotational drag coefficient C_d	$C_{dx}=1.330208E+01$	$C_{dx}=4.056928E-01$	$C_{dx} = 4.056928E-01$
	Lifting Force F_z	$F_z=4.552130E-01$	$F_z=2.851182E-01$	$F_z=7.573506E+00$
Model 2	Rotational drag coefficient C_d	$C_{dx}=1.021245E-01$	$C_{dx} =3.04478E-01$	$C_{dx}= 4.046527E+01$
	Lifting Force F_z	$F_z=1.552553E+01$	$F_z=2.197144E+01$	$F_z = 6.479037E+00$
Model 3	Rotational drag coefficient C_d	$C_{dx}=1.045578E+01$	$C_{dx} =7.43628E-01$	$C_{dx} = 5.570927E-01$
	Lifting Force F_z	$F_z=1.2128130E-01$	$F_z=2.851182E-01$	$F_z = -3.342777E-01$

Total resistive force

In the most complex, but most realistic, case where the bus is driven at varying inflation pressure, it is needed to calculate the instantaneous efficiency of the engine and the power required at each instant in order to work out fuel consumption and, ultimately, the tyre's inflation pressure contribution to consumption. Tyre rolling resistance coefficient is used to calculate the resistive force, Aerodynamic force developed by air ($\rho = 1.189 \text{ kg/m}^3$, area for model 1 = 2m^2 , model 2= 2.25m^2 , model 3= 1.85m^2), force of inertia and gravitation force of bus. The total resistive force ($F_{\text{tot res}}$) for each tyre model is given in table 4.5.

Table 4.5 Analysis of total resistive force

	Model 1 (N)	Model 2 (N)	Model 3 (N)
Rolling Resistive force $F_r = \mu_r \times F_z$	18962.5	2312.5	30525
Aerodynamic lifting force of rotational tyre $F_L = \frac{1}{2} C_L \rho_{air} A_{tyre} V_{bus}^2$	13.22	14.87	15.28
Force of gravitational ➤ $F_{gr} = F_z \times \sin \alpha$	$\sin \alpha = 0$ Level road	$\sin \alpha = 0$ Level road	$\sin \alpha = 0$ Level road
Total resistive force (F_{RM}) $F_{rm} = (\mu_r \times F_z) + F_L + F_{grv}$	=18975.752 N	= 2327.37N	=30540.28N

There are about 18975.752 N of resistive forces being exerted on the bus in case of a recommended tyre inflation model, 2327.37N for model 2 with over inflation pressure. In case of under inflation pressure the resistance force is reduced in rolling resistance between the tyre and road. The resistive force in model 3 is 30540.28N which is to other two models higher compared to the two models.

4.4. Overall contribution of tyre inflation pressure on the fuel consumption of Anbessa city bus

First, the contribution of tyres to the overall energy loss or fuel consumption in Anbessa city bus was estimated using the tyre pressure measured from survey and rolling resistance calculated. The tyres model accepts tyre inflation pressure and load on the tyres as inputs, to generate the aerodynamic drag and lifting force developed in each tyre inflation range. The overall fuel consumption of the bus in each model at various speeds was calculated. The results are indicated in table 4.4. The power used in each model is shown in figure 4.3.

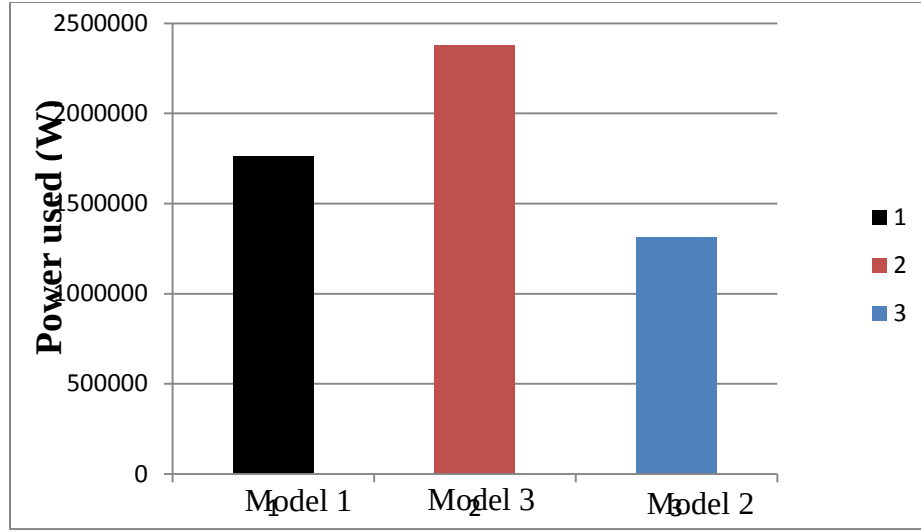


Figure 4.4 Power used in each model at a speed of 60 km/hr

Table 4.6 Power used in each model

Bus speed (m/s)	Power used on the model $P_{used} = ((\mu_r \times (F_z + F_L) \times V_{bus}) \text{ (kW) [17]}$		
	Model 1	Model 2	Model 3
10	414.541	5176908	436.083
15	662.402	168.031	737.449
16.67	751.22	226.41	853.408
20	958.969	392.748	1138.804
25	1320.479	762.070	1673.477

The above table shows comparison of power used on the bus in each model when moving with same speed, assuming that the coefficient of rolling resistance for all tyres on the bus is uniformly used to analyze the power used in each tyre model and fuel analysis.

This power used in different models is the overall result of rolling resistance effect and the effect of drag and lifting forces obtained from CFD analysis done on three models.

It is observed from the figure 4.3 that the net energy loss in model 3 which is under inflated tyre is 6.3% more than model 1 with recommended inflation pressure. But when we compare the net energy between model 2 and model 1, model 2 which is over inflation pressure saves 53.64 %

more than model 1 even though it has an effect on tyre age reduction The tyre will also be exposed to wear and damping effects.

For the realistic fuel consumption analysis done on a new bus given for test, the percentage of fuel consumption accounted by rolling resistance depends on:

- The speed and acceleration of bus used in the day trip considered that is constant 60km/hr.
- The vehicle's characteristics (mass, streamlining, internal friction, gear ratio) from specification.

Fuel used by each models

According to the Willans relationship of power consumed on the bus and required power from the specification we can analyze the exact fuel consumption of the bus in field. By adjusting the bus at a constant 60 km/h the engine speed is 1900 rpm (in fifth gear) using equation (2.7)

$$P_{consumed} = 2.23 \times P_{required} + 6.82 \times N_{rpm}$$

Table 4.7 Specification of bus

The bus data from specification	
Gross weight	18500kg
Fuel consumption	25L/100km(full load, on flat good road)
Engine Rated power	199kW/1900rpm

Now let us see the bus in Addis Abeba traveling condition in reality rather than the theoretical analysis and the fuel consumption used on the bus as tyre pressure varies or in there three inflation range but the inflation pressure is indicated by total load variation mean carrying capacity variation done on field. The bus can travel on an asphalt road at a constant 60 km/h, i.e.16.67m/s. There are about 18975.752 N (assumes that the coefficient of rolling resistance for all tyres on the vehicle is uniform 0.45 when doing model 1) of resistive forces being exerted on the bus in case of model 1. Different resistive force developed in each tyre inflation pressure ranges or in each model, this varies condition of resistive force and tyre pressure are a significant effect in real analysis.

The power required for the bus is by the real bus speed and total resistive force of model 1 is 751.22kW. At 60 km/h, the bus therefore consumes 751.22kW in one hour.

The bus engine energy value is 199kW per liter. When assuming for model 1 the bus 100 % engine efficiency, we would only need $\frac{751220W}{199000W} = 3.77$ liters of fuel for 60 kilometers. Realistically, for a 199 kW per liter rated engine power, consumption is around 17 to 20 liters per 60 km/hr.

We have: the bus consumed power is as follows

$$P_{consumed} = 2.23 * 751.22kW + 6.82 * 1900rpm = 1688.18 kW$$

The efficiency of the engine using equ (2.8)

$$\eta = \frac{P_{required}}{P_{consumed}} = \frac{751220W}{1688178.6} = 0.44$$

The fuel consumed with in given speed means at 60km/hr. is 1688.18kW in hour but the engine rated power is 199kW/liter. Then by dividing the power required during real motion to the rated

$$\text{Fuel consumption} = \frac{1688.18KW}{199KW} = 8.4 \text{ in } 60\text{km}.$$

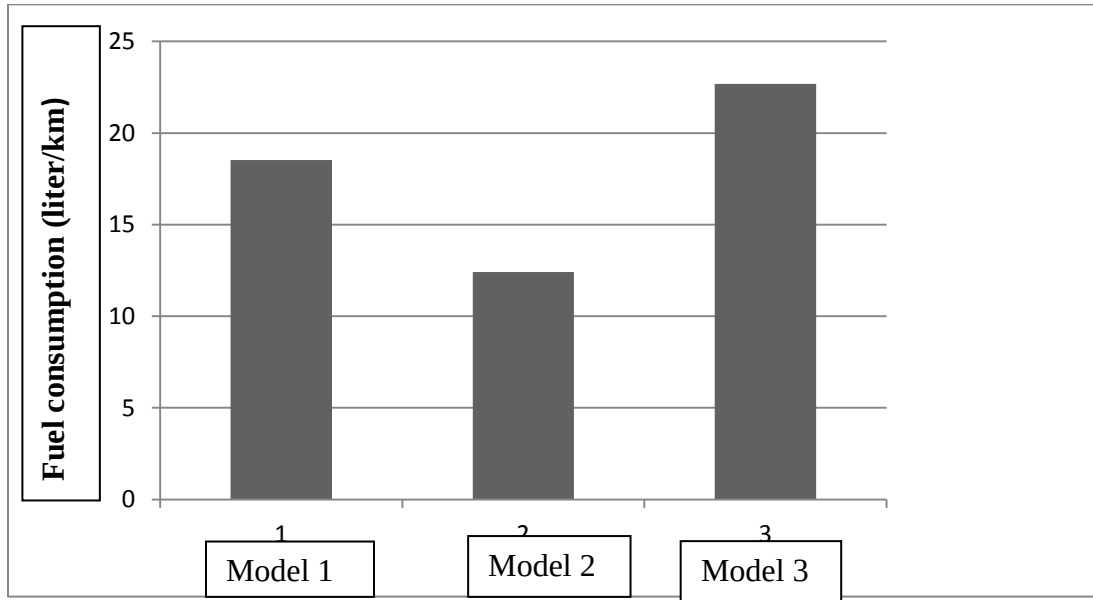


Figure 4.5 Fuel consumption in each model with same speed at 60km/hr.

Table 4.8 Fuel consumption in liter per km at different speed

	Fuel consumption (liter per 60km)		
Speed of bus (m/s)	Model 1	Model 2	Model 3
10	16.343	11.48	19.64
15	17.983	12.18	21.93
16.67	18.53	12.42	22.7
20	19.622	12.89	24.21

Now the contribution of tyres inflation pressure to the overall rolling resistance loss in a bus was estimated using the bus overall behavior, road condition and forward speed. The tyre models in a different tyre inflation pressure, load on the tyres and the rotational aerodynamic effect of tyre as inputs, among other parameters, to now the fuel consumption in liters/60 km as output.

Fuel consumption are indicated by using bar graphs as to now the amounts in percentage when the bus to cover the same distance 60km/hr. Let us see the fuel consumed when the bus inflated on the recommended pressure range it takes 0.308 liter per km. As a bus inflated under recommendation Model 3 is 0.378 liter per km as average which is 11.05 % of fuel is over consumed used as compared to model 1 when it move in a 60km/hr. However, it can also observe the Model 3 is used in tyre may be estimated 29.24% fuel consumption as compared to Model 2 over inflation pressure when it cover the same distance 60km. It is observed that the fuel consumption decrease by 9.74 % when the tyre pressure was increased from the recommended pressure of 0.83Mpa to 0.9Mpa, at given speed and distance. But more stress is developed and rolling loss also increased when the tyre pressure is over inflation pressure as Model 2. The bus's tyre inflation pressure variation affects the fuel efficiency and tyre performance.

4.5. Vehicle handling performance in different tyre inflation pressure

The ANSYS simulation of tyre model that uses the known operating conditions and assumptions about physical behavior of a tyre to predict the exact tyre phenomena on basis of deformation created on the tyre. As the bus is turning, the friction between the tyre and pavement surface restricts the lateral movement of the tyre and results in lateral deformation of the tyre and also

the longitudinal contact stresses on a pavement surface during braking and acceleration have similar magnitudes but opposite directions with forward stresses at braking and backward stresses at acceleration. This longitudinal contact stresses and lateral deformation of the tyres in equally inflated tyre models each case tyre inflation pressure can indicate the lateral and longitudinal force developed by slip angle variation occurred on tyre during cornering.

This simulation investigation of tyre pressure effects on vehicle handling performance of the Anbessa city bus.

4.6. Tyre Contact stresses

Now we can see the simulation of tyre stress distribution in each tyre models to predicted 3-D tyres contact stress developed because of the bus overall load and rotational rolling coefficient at the tyres and pavement interaction. The results show that the maximum stress occurred area and deformation created in tyre when the same applied force, forward speed and slip angle given with the three case in different tyre pressure.

Hence, the contact stress distribution is no longer symmetric with respect to the center plane and the distribution is different in a different tyre pressure.

Model 2 over inflation pressure

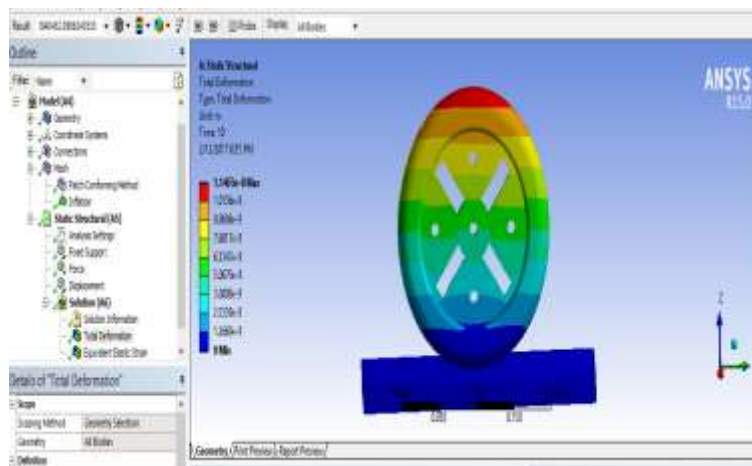


Figure 4.6 Stress concentrations on over inflation pressure

Model 1 recommended inflation pressure

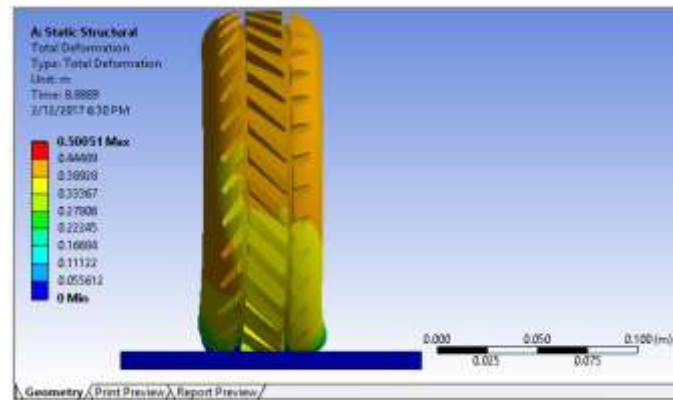


Figure 4.7 Stress concentrations on recommended inflation pressure

Model 3 under inflation pressure

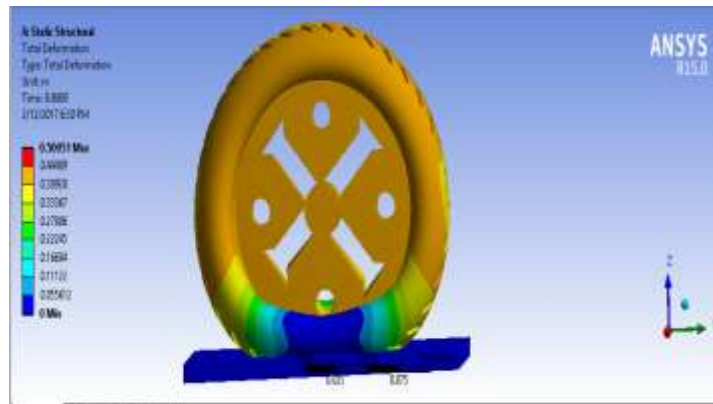


Figure 4.8 Stress concentrations on under inflation pressure

4.7. Tyre Forces

To investigate tyre inflation effects on lateral force, on Anbessa city bus (150kW engine, automatic transmission, rear wheel drive, rack/pinion power steering) with 295/80 R22.5 Horizon Addis tyres was numerically evaluated. The three tyre model configurations were: In this study where only front axle lateral forces are considered and the rear ones are neglected with respect to the front ones. The vehicle is driven at constant speeds or accelerates or decelerates slowly, avoiding the case of rough braking/acceleration.

The result of the bus lateral force analysis is with the mass 5700 kg of front axle, the bus moving velocity is 60km/hr. To simulate Anbessa city bus front tyres share the same rolling coefficients

in each cases means operating on different coefficient, tyre inflation pressure configuration, maximum steering wheel angle, maximum vehicle side-slip angle.

- Case I Model 1, $\mu = 0.44$ recommended inflation, tyre inflation 0.83Mpa
- Case II Model 2, $\mu = 0.07$ over inflation, inflation pressure 0.9Mpa
- Case III Model 3, $\mu = 0.73$ under inflation pressure, inflation pressure is 0.7Mpa.

4.8. Lateral force on tyre

Based on this investigation, it appears that difference in longitudinal and lateral forces can be directly generated by manipulating the tyre pressures.

Manufacturer recommended tyre inflation pressure should improve vehicle handling performance through the manipulation of lateral forces developed at the tyres.

To simulate and to see the lateral force variation of tyres in different inflation pressure same rolling coefficients are used for each model.

Model 1, $\mu = 0.44$ recommended inflation, model 2, $\mu = 0.07$ over inflation, model 3, $\mu = 0.73$ under inflation pressure. A Formula SAE tyre would have the cornering stiffness of around 734 N/° for tyre load of 1.5 kN [25].

The bus requires more steering effort to maintain the turning way for the under-inflated tyre in the model 3 up to 9000N is needed at the slip angle 8° . The maximum bus tyre slip angle, $\alpha = 8^\circ$ also increased due to the bus's reduced directional handling capabilities when equipped with under-inflated tyres. However, the cornering stiffness increase becomes negligible after $\alpha = 8^\circ$ (saturation point) for all models which are under inflated tyre fully inflated and over-inflated tyres.

$$\alpha = \frac{C_\alpha \tan(\alpha)}{\mu \times F_r}$$

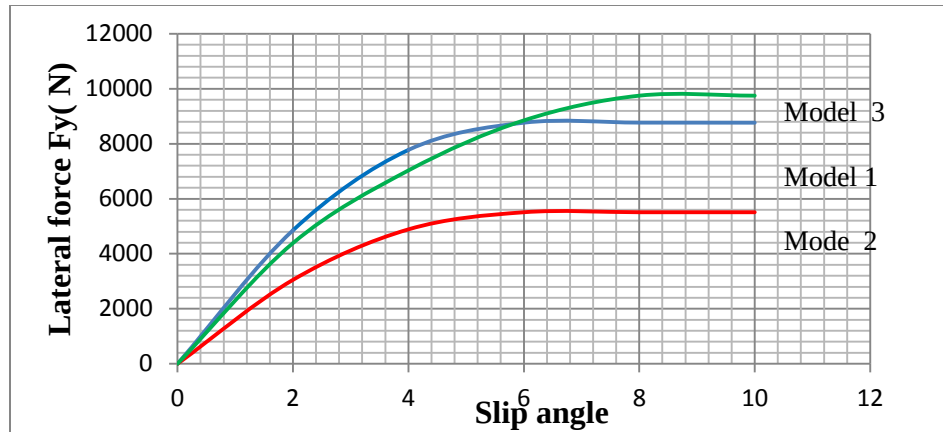


Figure 4.9 lateral force versus slip angle

In the case model 2 over inflation pressure, the maximum steering wheel suddenly occurred at slip angle 6° and increasing tyre inflation pressure than recommended the lateral force is reduced. Slip angle in the front greater than as compared to the rear. ($\alpha_f > \alpha_r$). The under steer gradient, ($K > 0$) over inflation which raised the bus's to under steer characteristics.

This may be attributed to the increase the bus front tyre cornering stiffness per over inflation which raised the bus's over steer characteristics.

A front tyre pressure reduction of model 3 (under inflation pressure) leads to small steering wheel angles because of the surface area contact large force is needed for steering. Slip angle in the front less than as compared to the rare. ($\alpha_f < \alpha_r$). The under steer gradient, ($K < 0$) over inflation which raised the bus's to under steer characteristics. Decrease in front tyre pressure than the recommended inflation pressure offer greater over steer.

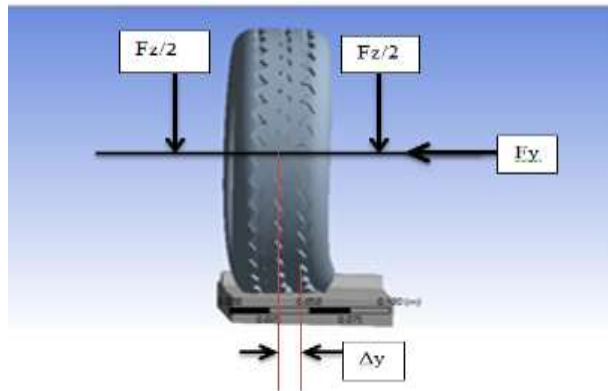


Figure 4.10 Lateral deflection

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1. Conclusion

In this thesis work the effect of tyre inflation pressure on the fuel consumption and handling performance is analyzed and investigated. The tyre models and tyre pressure and fuel consumption survey are done on the Addis Abeba city bus. The overall analysis is done by applying the loads of Addis Abeba city bus specifications. Analysis is done by applying different inflation pressure in each tyre model. The Tyre models material used for tyre is rubber and their dimensions are obtained ETRTO (the European Tyre and Rim Technical Organization) from Horizon Addis tyre manufacturing company. The contribution of tyres inflation pressure to the overall rolling resistance loss in a bus was estimated using the bus overall behavior, road condition and forward speed. The tyre models in a different tyre inflation pressure, load on the tyres and the rotational aerodynamic effect of tyre as inputs, among other parameters, to generate the fuel consumption in liters/60 km as output.

After analysis it was observed that the Model 3 (under inflation pressure) tyre contributed to nearly 11.05% more fuel consumption as compared to Model 1 (recommended inflation pressure) with equal distance travel and at same speed. However, it can also observed that Model 3 (under inflation pressure) used 29.24% more fuel as compared to Model 2 (over inflation pressure) when it covers the same distance which is 60 km. It is observed that the fuel consumption decrease by 9.74 % when the tyre pressure was increased from the recommended pressure of 0.83Mpa to over inflation pressure of 0.9Mpa, at given speed and distance. And also more stress is developed and rolling loss also increased when the tyre pressure is over inflation pressure as model 2. The bus's tyre inflation pressure variation affects the fuel efficiency and tyre performance.

In this paper, a vehicle's smoothly turning behavior has been investigated for various tyre inflation pressure cases. Decrease in front tyre pressure than the recommended inflation pressure offer greater over steer. A front tyre pressure reduction of model 3 (under inflation pressure) leads to larger steering wheel angles. In case of model 2 highly inflated tyres leads the bus under steer.

To use the recommended tyre pressures there should be a massive public education or awareness about the need to keep recommended tyre pressure at all times because when tyre pressure falls below the recommended value, the decrease in the pressure invariably leads to an increase in fuel consumption and highly affects vehicle handling performance. When tyre pressure increases above the recommended value there will be a decrease in fuel consumption but affects the vehicle handling performance.

5.2.Recommendations for future work

This study is initiated to investigate the physical influence of tyre inflation pressure on Addis Abeba city bus on the fuel consumption and handling performance. The model has the potential to represent the rolling effect, the rotational aerodynamic effect and fuel consumption in detail. But the Effect of temperature can be significant on viscoelasticity and inflation pressure, it is to be studied in detail.

Through this work, it also shows the vehicle handling performance and steering characteristics. A clearer trend of the influence of tyre pressure on the different parameters such as longitudinal forces and moments forces have not been established in detail. it is to be analyzed using other software's like Matlab Simulink etc .

This thesis work is a pre-study to control the fuel consumption occurred due to tyre inflation pressure by designing automated tyre inflation monitoring and rolling resistance control system on the bus, to maximize the fuel effective usage. The potential to do more on the stability and handling control system on the tyre during cornering or steering by using an adaptive steering feel requires a steering system with the possibility of quickly altering the steering ratio and servo assistance. Such systems are available today for modern cars and will probably be available for the city bus in the future.

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