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EFFECT OF NITROGEN FILLING ON TIRE ROLLING RESISTANCE AND VEHICLE FUEL ECONOMY

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EFFECT OF NITROGEN FILLING ON TIRE ROLLING RESISTANCE AND VEHICLE FUEL ECONOMY

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ABSTRACT

There are various losses associated with passenger vehicle that affect its fuel economy as it is being operated. These losses include engine, driveline, aerodynamic and rolling losses. While engine, driveline and aerodynamic losses are inherent with the vehicle due to large number of parts that go into assembling, rolling loss is associated with the vehicle tires and it is the only part of the vehicle that comes in contact with the road. The rolling resistance of inflated tires is an important component of resistance to vehicle motion and contributes to vehicle fuel consumption. Many research works have been focused on how the various tire parameters (e.g., load, inflation pressure and speed) affect rolling resistance so that fuel economy can be increased. Recent studies indicate that inflating tire with nitrogen can maintain proper inflation pressure and decrease the deterioration of the rubber. Therefore, the goal of this research is to explore the probability of using nitrogen inflated tires to improve vehicle safety, performance, and reduce operating cost.

In order to accomplish these goals, literature review was done to study the characteristics of tire and methods to improve the vehicle fuel economy and increase tire life. Based on this, a mathematical model was developed and refined to predict the rolling resistance of tires identifying the key parameters affecting them. Considering the possibility of inflating tires with nitrogen, the pressure sustainability of the inflation gas in tires at different operating conditions was tested. However, this does not represent the real driving conditions. Putting to test the tires filled with nitrogen under driving conditions would further help understand tire behavior and how this would affect the tire

contact patch area with time. Comparing the test results of nitrogen inflated tires with air inflated ones was performed to determine the importance of nitrogen inflation to cut down the cost spent on fuel and replacement tires.

Extensive shop testing was done at MARC (Michelin America Research Corporation) on different passenger car and truck tires. Qleak tests were conducted at room temperature for 16 days, while Sleak tests were performed at higher oven temperatures for about 28 days. It was observed that nitrogen inflation can maintain tire pressure approximately 35% to 55% better than air inflated tires for Qleak tests and about 29% to 35% better for Sleak test depending on tire type. In order to better understand the problem at hand, road testing was also performed on Wal-Mart truck fleet by inflating the tires with both air and nitrogen gases. The results demonstrated that nitrogen inflated tires improve tire life by about 50% and vehicle fuel economy by 23%. Considering these experimental results and extensive computer simulations, it was proven that nitrogen filling in tires help improve tire life and vehicle fuel economy.

DEDICATION

This thesis is dedicated to my parents, Venkataraman and Kausalya, and my brothers, Venkateshwaran and Bharath, who gave me strength to move forward towards something better, my project advisor Dr. Nader Jalili for giving me the opportunity to work on this project and for his guidance and advice all along, all my friends and colleagues, and all others who assisted and rewarded me along this course towards higher achievement.

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TABLE OF CONTENTS

Table of Contents (Continued)

Page

LIST OF TABLES

LIST OF FIGURES

List of Figures (Continued)

Figure Page

CHAPTER ONE

INTRODUCTION

Background

Rolling resistance of tire does affect the fuel economy of the vehicle it is attached to. For that matter, vehicle manufacturers strive hard to maintain an average fuel economy for the fleet of vehicles they sell each year. In order to meet the demands, these tires are often designed with a priority on reducing weight and rolling resistance and are molded with slightly thinner sidewalls, shallower tread depths and use low rolling resistance constructions and tread compounds. While the tire construction and material has a lower effect on the rolling resistance of the tire, parameters such as load (L), inflation pressure (P), and vehicle velocity (V) greatly affect rolling resistance in the long run.

Fuel economy of a vehicle is a direct measure of the resistance offered to its motion. These include overcoming inertia, driveline frictional losses, aerodynamic loss, losses due to uneven road grades and rolling resistance. It is important to understand how each of these elements influences the fuel economy of the vehicle. Taking rolling resistance alone into consideration, rolling resistance contributes to about 15% of the total vehicle resistance during city driving, while this contribution is about 25% of the vehicle resistance during highway driving [1].

Rolling resistance is primarily a function of the interactive forces acting at the road/tire interface. While axle load (Z) and velocity (V) contribute to the rolling force, tire inflation pressure determines the area of the tire that would come in contact with road during rolling. Hence, maintaining optimum tire pressure at all times would help reduce rolling resistance and improve tire life and vehicle fuel economy.

An over-inflated tire will have lower rolling resistance because the contact patch area of the tire decreases but will result in non-uniform wear along the centre of the tire tread. On the other hand, an under-inflated tire will have higher rolling resistance due to increase in contact patch area and will wear out faster along the outer edges of the tire tread. Recent research shows that tires filled with nitrogen have lower tire wear and rolling resistance as they can maintain tire pressure better than tires filled with dry shop air.

In order to optimize the tire wear and reduce rolling resistance, it is necessary to better understand the issue at hand. Hence, this research work aims at understanding the behavior of tires filled with air and nitrogen under static and steady-state rolling conditions. This would explain the influence of tire inflation pressure on rolling resistance, and hence, its effect on vehicle fuel economy and the overall operating cost.

Motivation

When a vehicle is driven on the road, the only parts of the vehicle that is in contact with the road are its tires and all the forces exerted on the vehicle by the road are transmitted only through the tires. These tires provide the forces which affect the dynamics and control performance of a vehicle. Hence, it is important to understand the tire characteristics to road inputs and optimize the performance to improve the vehicle fuel economy. The tire manufacturers also strive hard to maintain the balance between vehicle fuel consumption and optimal performance.

Many tire models have been developed in the past and also experiments were conducted to understand the tire behavior to road inputs in detail. One method to investigate tire behavior was carried out on a rolling tire using test rigs instrumented with tri-axial force transducer [2] to provide longitudinal, lateral and vertical stress measurements at the tire/ground contact patch. However, it is important to measure rolling force acting on a tire under real driving conditions to see how parameters such as inflation pressure, load and speed influence it. Finding a solution to optimize the tire contact patch area by improving the sustainability of tire pressure can have a positive effect on vehicle performance and safety.

It is well known that the tire grips and re-grips as it passes through the contact patch, i.e., the area of the tire that interacts with the road, which causes deformation of the tire. As the tire deforms, it dissipates energy in the form of heat and this dissipated energy is a measure of the tire's rolling resistance [3]. One way of reducing the heat dissipation in tires is through changing its construction as it is mainly caused due to internal friction of cross belts. While changing tire structure using different materials and construction techniques have a minor influence, it is the property of rubber that plays a major role in producing rolling force to tires. Hysteresis losses of the rubber material contribute about 90% to 95% [4] of the total losses due to rolling resistance. Hence, maintaining an optimum tire contact patch area for a longer time would help bring down the rolling resistance since this brings only lesser amount of rubber material into contact with the road surface.

Finite element simulation of the tire can be done to study the footprint area of the tire model for varying inputs of pressure and load and compare for both inflation types. This will give an idea of what is happening at the contact area of the tire simulating real driving conditions. Since the loss strain energy density [5] is the main cause of temperature rise in the tires, it is also considered as the overall dissipative energy transferred in the form of heat. Hence, thermal analysis of the tire would show the temperature distribution on the tire in the sidewall and crown area for varying loads, pressure and velocity.

It is observed from previous research works [6] that 30% increase in rolling resistance would increase fuel consumption by 3% to 5% depending on driving conditions and 1.5% to 4.5% of total gasoline use could be saved if all the replacement tires used had low rolling resistance. Hence, one of the most promising opportunities for saving money on fuel and replacement tires is to reduce the resultant rolling resistance. Equally promising and challenging is to find means to achieve this goal of improving vehicle safety and performance while cutting down money spent on fuel and replacement tires.

Research Objectives

The research work documented here is intended to achieve the following objectives:

1. Investigate the relationship between rolling resistance and various tire parameters including pressure, load, velocity as well as tire filling strategy.
2. Provide the technical support for the statement that nitrogen filling in tires do have a positive effect on the tire performance and vehicle fuel efficiency.
3. Successfully develop a tire model to perform static footprint analysis and check feasibility of conducting dynamic rolling analysis and validate the simulation results with that of experimental results.

Problem Statement

This research work aims at studying the possibility using an alternative inflation gas such as nitrogen to fill tires which would help reduce rolling resistance generated to vehicle motion. The tests conducted indicate the importance of reducing rolling resistance as it affects the fuel economy of the vehicle and tire wear. Computer simulations performed in parallel with experimental testing help validate the test results. The research conducted explains how using nitrogen to inflate tires can help cut down money spent on fuel and replacement tires.

Thesis Contributions

An important contribution of this research is finding alternative means of inflating vehicle tires that would help improve vehicle safety and handling while having a positive influencing effect on vehicle fuel economy and tire life. To begin with, a refined mathematical model is chosen that would clearly emphasize the influence of Load (Z), Pressure (P) and Velocity (I) on the rolling resistance of vehicle tires. In this research work, a number of tests and simulations were performed which helps us understand the behavior of tire while using nitrogen gas to inflate them. The simulations give an insight of how nitrogen and air filled tires react to variable input parameters and also show the temperature distribution along the tire sidewall and the crown region. The results presented here not only prove that nitrogen inflation is a good alternative but also explain how this can help save money in a long term basis. The rolling resistance and tire wear values obtained from experiments help justify the probability of using nitrogen as inflation gas in tires to improved performance and safety.

CHAPTER TWO

LITERATURE REVIEW

Introduction

The research work presented is aimed at reducing tire rolling resistance by inflating truck and passenger car tires with nitrogen gas which helps improve vehicle fuel economy and tire life while cutting down the overall cost. All the works which most directly contributed to the research presented have been concisely summarized in the following sections.

Inflation Pressure and Tire Forces

It is important to study the inflation pressure characteristics of a tire and how they contribute to the fuel consumption of a vehicle. While various factors such as tire construction, load and vehicle velocity contribute to the rolling resistance of tires, inflation pressure plays a major role in determining the contact patch area as it is the only part of the vehicle that comes in contact with road. Right pressure can help maintain optimum contact patch area and reduce the opposing forces to rolling motion. The various material used and orientation of belts in tire construction affect the manner in which the forces are transmitted in the tire/road interface. The following section briefly summarizes some of the research works done on energy conservation and the forces acting on a pneumatic tire.

Tim and Russell [7] modeled the fuel consumption of trucks using AVL-CRUISE software showing the effect of various factors affecting fuel economy of the vehicle including engine, gear train and tires. The results presented indicate that fuel savings of 1.40 to 1.62 L per 100 km can be expected per kg/T reduction in average rolling resistance coefficient of the vehicle. The experiments and simulations were conducted for various driving cycles which indicate different driving conditions. Representation of fuel consumption model with data points over time helps predict fuel consumption of trucks with change in rolling resistance of the tire. They developed a mathematical model to represent fuel consumption as a function of distance traveled for each driving cycle. Although the model developed by Tim and Russell do not speak about the tire as a test model itself which would represent the involvement of tire pressure, load or the velocity, the results presented show the influence of rolling resistance on the fuel economy of trucks.

Joshua and Jason [8] presented a report on preliminary study of tire pressure on randomly chosen vehicles highlighting the importance of maintaining proper inflation pressure. The report discussed how tire inflation pressure influences vehicle safety, fuel consumption and green house gas emission. Overall, the survey found that about 26% of passenger cars and 29% of light trucks had pressure, in at least one tire, 25% below the pressure recommended by the vehicle manufacture. Following the survey, the authors found out that for every 10% decrease in rolling resistance, the fuel economy could be increased by about 1% for urban driving. It was found that inflation pressure increases the stiffness of the tire and influences the contact patch area.

In the report published by the Tire Retread Information Bureau [9], the author explains that using nitrogen as inflation gas help tires retain more of its original properties. The advantages of using nitrogen gas to inflate tires are explained and it is concluded that 100% pure nitrogen inflation can reduce tire wear and improve fuel efficiency. The author concludes by listing out the various advantages of using nitrogen including environmental effects as improved tire life reduces the number of replacement tires.

In support of the report by Tire Retread Information Bureau [9], Konrad Mech [10] in his report explains how oxygen molecules in air inflated tires are responsible for the pressure drop over time. Reduced tire failure rates are demonstrated during a field trial conducted over 7,500,000 miles. The report investigates how the double bonds in tires are broken down due to oxidation of air inflated tire and the oxygen molecules penetrate up to the outer tread band of the tire. This is the reason for pressure drop in tires. The survey found that frequently topping the tires with oxygen causes the tire to degrade due to oxidation whereas not maintaining tire pressure causes fuel penalty of about 2% to 5% per 10 psi drop in inflation pressure. The author sums up his observations by saying that nitrogen inflation can have benefits such as maintenance of correct inflation pressure, extended casing life, reduced tire failure rates and elimination of condensed water in tires.

A report published by Air Products [11] indicates that water molecules present in shop air are heated up during rolling conditions and hence increase the overall pressure of the tire over time. This increase in tire pressure causes further diffusion of oxygen molecules through the tire and increases rolling resistance. It is observed that nitrogen molecules are bigger although they are lighter than oxygen molecules. Based on the observation, it is concluded that nitrogen inflation can reduce rolling resistance and tire wear compared to traditional air filled ones.

While the previous research found the importance of inflation pressure to reduce rolling resistance, Dihua *et al.* [12] presented their research based on the forces acting at the tire contact patch to model rolling resistance of rolling tires. Their derived model describes the change process of vertical load and friction force distribution from a static to rolling state. Their tire model was partitioned into many smaller elements and the forces acting on these elements at the contact patch area were calculated using force balance, rolling kinetics and road constraint conditions. In their mathematical model, structural damping transformed from viscous modal damping is introduced as rolling resistance is mainly caused by the effect of tire hysteresis damping. The developed model eliminates the symmetry of the contact patch with the front part of the contact patch area being larger than the rear. The results show decrease in rolling resistance with increase in inflation pressure and decrease in load which is consistent with the objective.

Wong [13] represents the general forces and their directions to be considered while analyzing tire characteristics. His work explains that a tire has to be examined in its own coordinate system due to the complexity of the tire model and the forces acting on it. It shows in detail the constructional differences between radial and bias-ply tire with respect to the orientation of the belts. It is interesting to note how the forces act at the road/tire interface for soft and hard grounds and the influence of tire pressure on rolling resistance depending on ground hardness. It is observed that higher inflation pressure reduces rolling resistance on a hard surface while producing higher rolling resistance on soft ground. A mathematical model is given to calculate the coefficient of rolling resistance for passenger car and truck tires depending on the velocity of travel. The author in general explains the behavior of tires based on surface hardness, tire construction and inflation pressure.

Guan *et al.* [14] developed an FEA model of 195/60R14 radial tire using MSC.MARC software to study the influence of belt cord angle under various rolling conditions. The Mooney-Rivlin constitutive theory was used to describe the hyper elastic model, exhibiting material and geometric non-linearity. The authors explain how the stress and strain states change at the contact patch area based on the construction of the cords of the rebar material. In their work, tire was analyzed by mounting it on a wheel and contacting it with a rigid road surface. The results show that the largest normal stress acts at the front of the contact patch and increases with increase in belt cord angles, moreover, the length of the patch along circumferential direction decreases with increase in belt angles. Likewise contact patch area forces during braking and friction distributions are also studies. The work helps get an insight of the influence of belt cord orientations and tire construction on contact patch area forces. It is important to understand the tire characteristics before analyzing the influence of any single parameter on the rolling forces acting at the road/tire interface.

Tire Characteristics and Rolling Resistance

Tire is one of the most complex structures as it is made up of a number of parts that exhibit both material as well as geometric nonlinearities. Past research works have proved that hysteretic property of the tire rubber material is one of the primary causes for tire rolling resistance. As the tire grips and re-grips the road surface during rolling, the rubber material bends and energy is expelled in doing work. Many models have been put forth to determine the energy expelled during rolling. The following describes concisely a number of works that were used in the research work presented.

Pillai [15] presented a model to verify that the total energy loss in tires due to hysteretic property of the tire is same as that calculated using rolling resistance method. In his work, he uses an experimental setup to measure the hysteresis of the rubber tire by loading it on a load cell and measuring the energy lost during one loading and unloading cycle. The developed mathematical model to measure the hysteretic loss per hour of travel is given as a function of number of footprint contacts made per tire revolution. The value of energy loss calculated from the experiment was the same as the energy loss calculated using rolling resistance methods.

Shida *et al.* [16] performed a static practical rolling resistance simulation method for tires with easy input data preparation and short computation time having adequate accuracy. In this simulation, a phase lag between stress and strain profiles is introduced to compute the hysteresis of rubber. A model for the rolling resistance of tire was introduced as a function of total energy dissipation of the tire and the traveling distance. The authors represent the sinusoidal expressions of stress and strain which is in terms of variation of time to be in terms of an angle representing the elements along the circumferential position of the tire. From the simulations it was observed that the calculated results match well with the observed results in the pressure range of 150to250 kPa. Similarly, the results are good for loads ranging between 2.5 to3.5 KN. The report also shows the relation between the tire width at the contact patch and how this affects the rolling resistance. All the results show that such a simulation can be used to validate and predict the rolling resistance of tires.

Luchini *et al.* [17] proposed a new directional increment hysteresis theory to describe the hysteretic behavior of carbon black filled rubber. This theory includes an incremental formulation to deal with the non sinusoidal cycles within tires. As hysteresis is a function of strain and temperature, an alternating octahedral shear strain (AOSS) was chosen as it had 3D strain relationship. The authors include another octahedral shear pre strain term to overcome the shortcoming with the initially proposed model. Based on the hysteresis found out from the above models, the rolling resistance is given by the energy spent due to hysteresis to the distance traveled or the circumferential distance of the tire when the work is done. Hence, the rolling resistance can be calculated per cycle of tire travel. Based on the results this proposed model gives more accurate results to the previous models developed as they were based on visco-elastic property alone.

P. R. Willet [18] presented a paper on hysteresis which states that the total rolling resistance of a tire is the sum of rolling resistance due to hysteretic losses and rolling resistance due to inertial distortion of the tire. The two types of deformations acting on the tire at the contact patch are bending deformation due to vertical deflection of the tire and the compressive deformation due to the loading on the tire. The rolling resistance as a result of hysteresis due to carcass rolling, tread bending and compressive losses were separately computed. Based on the results it was concluded that hysteresis effect of tire can be divided into bending and compressive components and although the temperature gradient exists within the tread of the tire, they remain constant while tire is in a state of equilibrium.

Tae-Sok *et al.* [3] investigated the energy loss in rolling tires and outlines that temperature increases in rolling tires is dissipated as heat which is a measure of rolling resistance caused by the hysteretic property of hyper elastic rubber material. In this work, the calculated values are compared with the measured values where thermocouples are implanted in the shoulder of the tire to measure heat dissipated during rolling. The loss and storage modulus of rubber tire are calculated from the phase lag of stress with respect to strain in the material. A mathematical model to calculate the rolling resistance of tires is developed from the strain amplitudes measured during finite element simulation of the tire. A 2D model is used to calculate the temperature distribution on the sidewall and crown while a 3D model is used to calculate the strain amplitude components during inflation and loading. The simulation results match well with the experiment results. From the results obtained it is concluded that about 63% of the total energy is generated in the tread and bead bundle and plies contribute only 10% each.

Lars and Tony [19] proposed that the coefficient of rolling resistance does not depend on only velocity, but tire temperature plays an important role in real driving conditions based on road conditions. Their model included a differential equation for tire temperature which uses the relation between momentary temperature and stationary temperature as input. It was observed that rolling resistance decreased with higher speeds because at higher speeds the tires were warmer and inflation pressure was higher.

However, when the vehicle velocity is reduced, the rolling resistance does not immediately fall because it takes a while for the tire to cool down and observe a reduction in inflation pressure. In this model, the coefficient of rolling resistance is given as function of velocity and temperature. A truck propeller shaft is fitted with sensors to calculate the torque and velocity of the truck to calculate rolling resistance at various speeds. This model was compared with the new model taking tire temperature into consideration. The temperature at the tire shoulder is the same as the inflation gas temperature. The new model agrees well with the traditional model of considering rolling resistance to be a function of velocity alone.

George Komandi [20] evaluated the rolling resistance force by saying rolling resistance is essentially a moment, but an active force is needed to move the wheel and this force acts at the axle of the towed wheel and at the perimeter of the driving wheel. He went on to describe the peripheral force based on the Coulomb's equation acting on a running gear. Due to inadequacy of detailed analysis this was further based on the well known equation of Janosi's which describes the peripheral force as a function of contact area, load, friction in contact patch and tangent modulus of shear stress. Deriving from various observations, the equations were simplified to develop a model for the moments at the driving and driven wheel separately. These were based on the forces acting at the axle and on the peripheral forces on a wheel. Although these models were consistent with all previous models developed, they did not represent the influence of various factors that affect the rolling resistance of tires.

Mathematical Methods

Based on the literature survey conducted above, a mathematical model was carefully chosen to include the effect of load, velocity and inflation pressure in calculating the rolling resistance of tires. The chosen model was further refined by choosing constant values of vertical load and speed and replacing them in the equation. By doing this it was possible to find the effect of inflation pressure on rolling resistance and compare the values for both air and nitrogen inflated tires. The models used from past research works are explained in the following section.

Parmeet [21] developed a model that represent rolling resistance data over a range of speeds and can be used to predict rolling resistance at various load, pressure and speed combinations. The author explains that the current model used for calculating rolling resistance included a number of regression variables and although the model provided good mathematical description of the data, it was not appealing from the point of physically describing the relationship between rolling resistance and independent variables like load, speed and pressure. Hence, a new model is proposed that provide a good physical description of the phenomenon including the independent variables that influence rolling resistance. This was universal and could be used for different types of tires from passenger car to truck tires. The exponents and constants in the model can be easily found out by using nonlinear regression or re-arranged into simpler form to perform multiple linear regressions. The author analyzes two models and compares the rolling resistance values to find out which gives better accuracy at he extremes of the speed curve. Finally, a new and simple model is developed with regression constants and coefficients that are easy to see and provides a better description of the influence of physical factors such as load, speed and pressure.

Parmeet and Sid [22] presented a paper that explores alternatives, defines new parameters and proposes a new methodology for comparing tires using data generated as per J2452 standard. They developed two new parameters namely mean and standard mean equivalent rolling force (MERF and SMERF). These models could be used for other reasons such as specifying design targets that represent contribution to rolling resistance. The MERF for a tire at a given load/pressure condition is defined as the average of all rolling resistance values corresponding to every single speed-time point in a fixed driving cycle. This helps measure the rolling resistance at each speed by the length of time spent at that speed during a cycle. In general, MERF is represented as the weighted average of urban and highway MERF cycles. SMERF is nothing but the MERF for that tire under standard load and pressure conditions which may be different for both passenger car and truck tires. This is used to compare rolling resistance of tires over a range of speed with standard load and pressure readings. These two models were developed from previous model by Parmeet [21].

Tire Modeling

A finite element model of Michelin 275/80R22.5 tire was created to analyze the tire characteristics based on the influence of inflation pressure and load. The tire was mounted and inflated and footprint analysis was conducted in an attempt to measure the hysteresis exhibited by tire rubber. Drawing from many sources, ABAQUS V6.7 was used to model and analyze the tire as it had various capabilities to precisely develop the various materials used in tire construction. The literature survey conducted based on finite element modeling using ABAQUS is explained in this section.

The ABAQUS Technology Brief report published by SIMULIA [23] discusses about the capabilities of ABAQUS software to run various analysis on tires. As tire analysis is very complex and requires large computational time, this report talk about various features that could be implemented to improve accuracy and reduce computation time. All the belts and cords that are used can be modeled as reinforcements. The rebar reinforcement is used to precisely model the belts with respect to material orientation. The author explains how the analysis can be split into various steps and the appropriate features to be used. Overall, the report defines the capabilities of ABAQUS in handling tire analysis and various tips as to how the computation time be reduced while improving accuracy.

Zamzamzadeh and Negarestani [24] conducted a finite element analysis on a 205/60R14 tire using ABAQUS code to simulate the tire interaction with the road. First, a 2D model was created and then a full 3D model to simulate footprint loading. Various hyper elastic models were compared and finally Arruda-Boyce model was chosen to give the best fit for the rubber material tested in the laboratory. The tire was modeled, mounted on the rim and inflated and made to contact with a rigid surface to find out the stress and strain distribution at the contact patch area. The analysis was started with rim mounting and inflation analysis on a 2D model and the stresses at the bead area were recorded. Then, a full 3D model was created to study the force in the footprint region.

Different materials were chosen for different parts of the tire and were meshed together to develop a uniform FEA model. The footprint loading results were plotted and helped predict the forces depending on the inflation pressure, load and velocity of the tire. The results were consistent with the objective in investigating the scope of predicting tire behavior using ABAQUS code. The simulations included both static state and dynamic rolling analysis.

Yeong-Jyh and Sheng-Jye [5] developed a finite element model of a tire using ANSYS to predict the temperature build up in the tire and related that to the rolling resistance produced. The authors develop the tire model similar to previous research work discussed, and used the principle of tire hysteresis to predict the heat generated. A dynamic rolling analysis was performed to predict the heat generated and this was particularly helpful in determining the influence of speed on rolling resistance. The tire model generated was relatively simple in geometry yet was good enough to conduct both static and rolling analysis to find the footprint force and the heat generated on the tire shoulder. It was observed that hysteresis effect increased for increasing loading and decreasing inflation pressure. The amount of heat transferred from hysteresis energy loss also increased with increase in speed. Based on the observations it was concluded that inflation pressure plays an important role for temperature rise and increase in inflation pressure reduces the effect of tire hysteresis and this was consistent with the objective of the research work done which is to be explained in the following chapters.

All the research papers and models that had been discussed in this chapter were useful in determining the primary objective of this project and also in understanding the tire characteristics. The experiments conducted and the development of the tire model evolved from the results and observations of the literature survey conducted. The following chapters will in detail explain the various stages of the project along with the results to prove that nitrogen inflation in tires can improve fuel economy and decrease tire wear which ultimately helps cut down the overall cost.

CHAPTER THREE

TIRE PARTS AND CONSTRUCTION

Introduction

Tire 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 tire behaves to various road inputs. The focus area of this research is to determine the effects of nitrogen filling in tires in order to improve vehicle safety, performance and fuel economy while reducing tire tread wear. Studying the different parts of a tire is necessary to see how they influence vehicle ride and safety.

There are mainly two different types of tires; namely, Bias-ply and Radial-ply tires, which differ in their construction and belt orientation. In a Bias-ply tire, the belts are oriented at an angle between 30 degrees and 55 degrees with respect to the centerline of the tire, while Radial-ply tires have belt orientation of about 90 degrees with respect to the centerline running from the centre of the tire to the outside in a radial pattern [25]. Nowadays Radial-ply tires are widely used as they outperform Bias-ply tires in a number of ways. Radial-ply tires provide better traction due to flatter and more stable crown area and a larger footprint area. The pressure applied due to load is also evenly distributed over the contact patch area which results in even wear out of the tire tread unlike in a Bias-ply tire where the outer region of the tire wears out faster than the centre. The tire used in the following simulations and testing is also a Radial-ply tire: Michelin

275/80R22.5 (tread pattern XZA). The following section explains in detail the Radial-ply and Bias-ply tire construction and the various parts that go into making it.

Tire Construction

The construction of a tire goes much deeper than what it appears on the outside surface. The body of a tire is usually referred to as the casing and is composed of multiple layers, which are called plies or belts. Belts under the tread give the tire strength and robustness, preventing the rubber tread from separating, and provides resistance to puncture. The materials used as belt-plies included rayon, nylon and polyester, with rayon more commonly provided as original equipment and nylon being offered as an extra cost option. The tires also have a lining of steel belt under the tread layer to improve the stiffness. These layers of belts or plies help in transmitting the load from road input on the tread layer, to be evenly distributed to the tire's side walls so that the tire can maintain its shape needed for rolling. Figure 3.1 represents the cut section view of a tire which gives a clear idea of its construction and the different cross layers that are placed in order below the tire tread region.

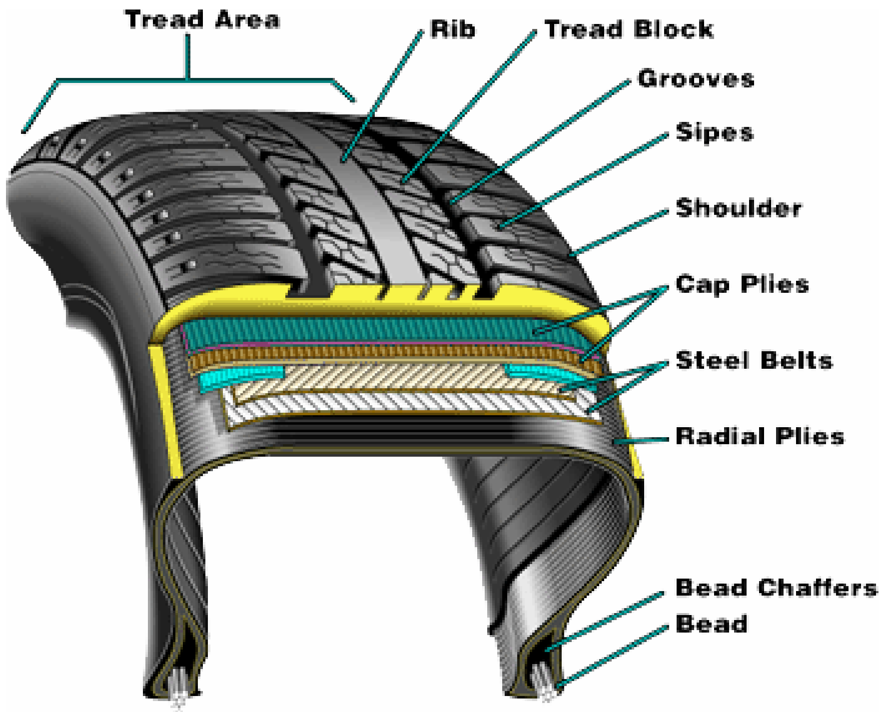

Figure 3.1: Cut section view of a pneumatic tire [26]

Bias-Ply Construction

As the tire casing is being constructed, the various layers (plies) are laid on top of each other in pairs. The innermost plies are normally placed at a 45 degrees angle, or bias, which means the plies are placed diagonally to each other, forming an "X" as they run across from one bead of the tire to the other (inside edge to outside edge). The outermost plies run lengthwise around the circumference of the tire. The purpose of this is to provide additional strength to the tire. This type of tire construction makes the sidewall area of the casing very strong, which allows the tire to support more weight. The tread area of bias-ply tires is very firm, and this design ensures good contact of the tread with the road. In fact, the design of this type tire can cause a very firm, even harsh ride. In addition to the ride characteristics, this type of construction does not flex very much, which increases rolling resistance and additional heat as the tread area of the tire contacts the road. This heat can build up to a point where it actually causes the tire to wear faster than normal, and is compounded by an under inflated condition, as well as poor vehicle alignment. Bias-ply tires are also prone to developing flat spots, especially if the vehicle sits for extended periods of time [27].

Radial-Ply Construction

Radial-ply tires are constructed in many ways much the same as bias-ply tires, with a couple of notable exceptions. The innermost plies on a radial tire are not angled as much as bias-ply tires. Radial plies normally have only a 2 degree or lesser angle to the plies, which makes them concurrent to one another, running sideways across the tire from bead to bead. They usually run at an angle of 90 degrees to the centre line of the tire. The belts in a radial-ply tire are normally steel.

Radial-ply tires are more flexible than bias-ply tires, which allow the tread and sidewall of the tire to conform to the contour of the road better, especially during cornering. The result is reduced rolling resistance, improved handling and traction under all conditions, and a reduction in heat build up, when properly inflated. Due to improved traction, tread wear of the tire is uniform. The reduced rolling resistance of radial-ply tires also allows for a notable increase in gas mileage. Radial-ply tires are less likely to fail due to blowout, and are more resistant to puncture when kept inflated at proper pressures. The greater flexibility also allows for a lower aspect ratio, which is covered below. Figure 3.2 shows the contact patch produced by radial and bias-ply tires.

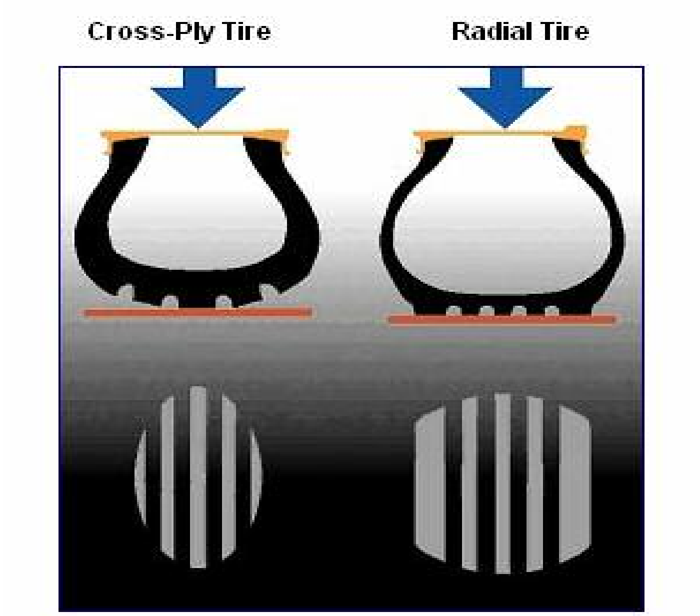

Figure 3.2: Foot print area of bias and radial-ply tires under axial loading [27]

Tire Sizing and Aspect Ratio:

Aspect ratio is defined as the ratio of the tire height to the width of the side wall. Let us consider the truck tire, Michelin 275/80R22.5, which is used in this research for experimental testing and simulation. The numerals mentioned above refer to the size of the tire used.

The first number refers to the width of the tire in millimeter measured from one end of the sidewall to the other. Hence, in this case the width of the tire is 275 millimeter or 10.83 inches. The second number represents the aspect ratio in percentage. Hence, the aspect ratio is 0.80. Equation (3.1) is given to determine the height of the tire using the aspect ratio [28].

$$\text{Width} \times \text{Aspect Ratio} = \text{Section Height} \tag{3.1}$$

The section height is 220 millimeter or 8.67 inches. The last numeral in the tire size is the diameter of the wheel in inches. Equation (3.2) gives the diameter of the tire.

$$\text{Combined Section Height} + \text{Wheel Diameter} = \text{Tire Diameter} \tag{3.2}$$

Therefore the dimensions of the Michelin tire 275/80R22.5 are given in Table 3.1.

Table 3.1: Dimensions of the tire under study

PARTAMETERS	DIMENSION	
	millimeter	inch
Section Width	275	10.83
Section Height	220	8.67
Wheel Diameter	571.5	22.5
Tire Diameter	1012	39.84

CHAPTER FOUR

ROLLING RESISTANCE OF PNEUMATIC TIRES

Introduction

Rolling resistance of inflated tires is an important factor that contributes to the fuel consumption of a vehicle. As the wheel goes round during vehicle motion, the tire is deformed to make contact with the road. All the forces required for acceleration, braking and cornering are transmitted through this contact patch. As it is deformed, the tire also absorbs road surface asperities and it is the tire's ability to be deformed which ensures grip and comfort. The work done in deforming the rubber compound during rolling is dissipated in the form of heat energy [3]. This energy dissipation is the primary source of rolling resistance of rolling tires.

The rubber compound in tires is primarily a hyper-elastic material which exhibits both material as well as geometric nonlinearity. This can cause considerably large deformation upon application of a force. As the vehicle travels on the road surface, the tread grips and re grips the road surface in the contact patch and this causes a radial deformation of the tire during travel. This causes hysteresis of the rubber compound where strain leads stress. This means that for a small force applied, the magnitude of deformation is more than any other material in the tire for the same amount of force applied. This phase lag between stress and strain causes the rubber to store energy in the form of strain energy potential which is dissipated as heat energy during rolling [5].

The rolling resistance of a free rolling tire is mainly caused by the internal friction in the rubber and cord, while the slip in the contact zone and the windage losses at moderate speeds are of less importance. The various factors influencing rolling resistance is represented as follows [4]:

1. Friction between tire and road : 2% to 10%
2. Air resistance, circulation in tire and on outside air : 1.5% to 3.5%
3. Internal hysteresis : 90% to 95%

Arbitrary Forces Acting on a Vehicle

All forces and moments are normally defined as they act on a vehicle under arbitrary conditions, based on the application of Newton's second law. Consider the vehicle as shown in Figure 4.1, in which most of the significant forces on the vehicle are shown, where W is the weight of the vehicle acting at its central gravity (CG), W_f and W_r are the normal forces on the front and rear wheels respectively, F_{xf} and F_{xr} are the traction forces on the front and rear wheels, R_{xf} and R_{xr} are the rolling resistance on the front and rear wheels, DA is the aerodynamic force, R_{hz} and R_{hx} are vertical and longitudinal forces acting at the hitch point.

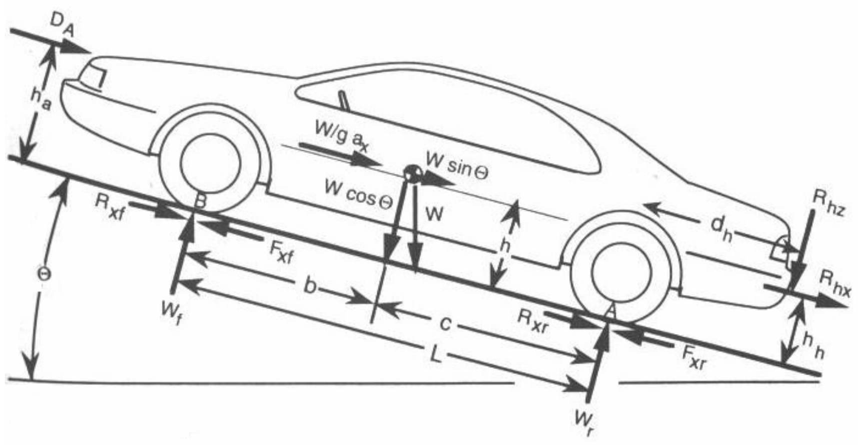

Figure 4.1: Arbitrary forces acting on a vehicle [29]

An Overview of Rolling Resistance

The tire Rolling Resistance (RR) is essentially a moment, however, an active force is needed to move the wheel forward. As a result, this force acts in the travel direction at the axle of a towed wheel and at the perimeter of a driving wheel. Certain fundamental equations are established at an early stage in the development of the discipline. In an attempt to determine the peripheral force acting on a running gear, Coulomb's equation was used by vehicle researchers [[20].

$$F_k = \mu.Q \tag{3.1}$$

where, μ is the frictional coefficient and Q is the vertical load.

This equation was found to be inadequate for a detailed analysis of cross-country motion. Researchers working under Dr. Bekker's supervision at the Land Locomotion Laboratory progressed to develop a better equation. As a result, Janosi's well-known equation was published in 1961 [30]:

$$F_k = (Ac + Qtg\phi)\left[1 - \frac{K}{sL}\left(1 - \exp\left(\frac{-sL}{K}\right)\right)\right] \tag{3.2}$$

where A is the contact area, c is the cohesion, Q is the vertical load, ϕ is the angle of internal friction, K is the tangent modulus of the soil-shear stress vs. deformation curve, s is the slip, and L is the contact length.

There is another interpretation according to basic mechanical principles based on the rubber material property as discussed before. The RR of tires on hard surfaces is primarily caused by the hysteresis in tire materials due to the deflection of the carcass while rolling. As a result of tire distortion, there is a difference in the normal pressure in the contact patch are. The normal pressure in the leading half of the contact patch is higher than that in trailing half. This causes the tire to slightly bulge in the leading edge and stretch in the trailing edge in the direction of rotation. As a result, the center of normal pressure is shifted in the direction of rolling. This shift produces a moment about the axis of rotation of the tire, which is the rolling resistance moment. In a free-rolling tire, the applied wheel torque is zero; therefore, a horizontal force at the tire-ground contact patch must exist to maintain the equilibrium. The resultant horizontal force is generally known as the rolling resistance (see Figure 4.2, [12, 13]).

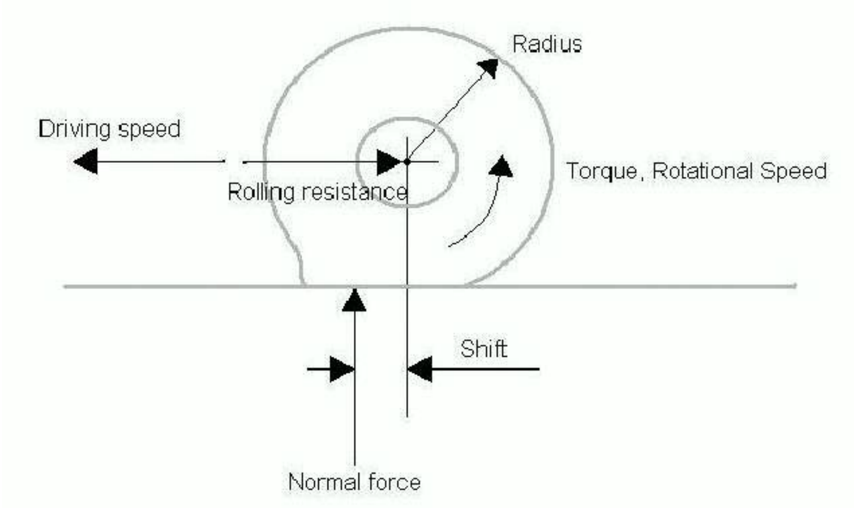

Figure 4.2: Shift in normal pressure of a rolling tire [13]

In Figure 4.2, assuming that F_r is the rolling resistance force, C_r is the coefficient of rolling resistance and R is the radius of the tire, then it is natural to define C_r as follows:

$$C_r = \frac{F_r}{R} \tag{3.3}$$

C_r depends on many variables including the operating conditions (inflation pressure, tire temperature, vehicle speed wheel adjustments) and the structure of the tire (construction and materials).

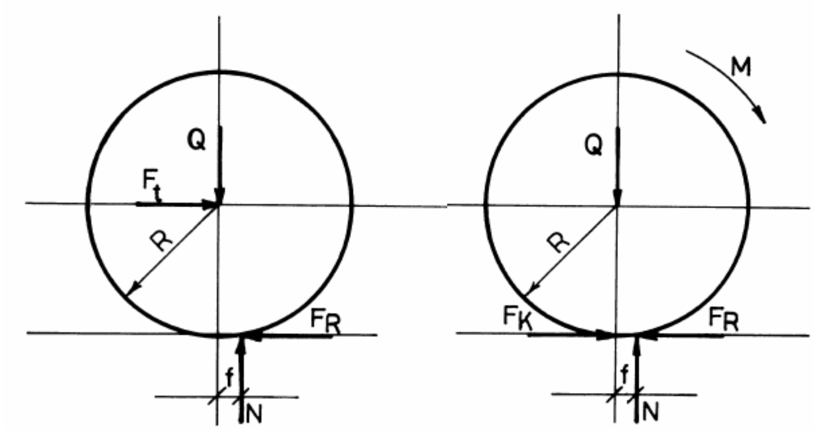

Figure 4.3: Mechanical relationship between towed and driving wheels:
a) Towed wheel, and b) driving wheel [12].

Figure 4.3 shows the rolling force acting on the driving and the towed wheel [12]. The forces acting on the towed and the driving wheel of a vehicle are shown below as explained by the author [12]. The mechanical characteristics of towed and driving wheels are identical. One can transfer the static analysis from one case to the other. Figure 4.3 a) shows a wheel which rolls over terrain. Force F_t is acting on the wheel, which pushes it in the direction of travel. The reaction force created by the deformation is represented by two components. So, for a towed wheel we have,

$$F_R R = fN \tag{3.4}$$

where, F_R is the RR, R is the radius, f is the pressure shift in direction of rolling and N is the reaction force.

F_t is the force required to tow a rigid wheel in deformable soil, F_K is the peripheral force, and Q is the Load. The force needed to move the wheel forward can be calculated from the equation of moment equilibrium,

$$F_t = fQ / R \tag{3.5}$$

where $N = Q$ and $F_R = F_t$.

Figure 4.3 b) shows the moments and forces acting on a driven (or driving) wheel. This represents the static conditions under which a wheel operates while moving itself in deformable soil.

The forces needed to roll a driving or a towed wheel is of equal magnitude, if the conditions are the same. The sense of the force vector points in the direction of travel. Therefore, rolling resistance occurs at the center of a towed wheel, which is $F_t R$, and at the bottom of the driving wheel, which is $F_K R$, the latter being the peripheral force.

Rolling Resistance and its Relationship to Pressure (*P*), Load (*Z*) and Speed (*V*)

Research shows that the coefficient of rolling resistance for pneumatic tires is dependent on hysteretic loss from tire deformation which is affected by the vertical force applied to the tires and the tire inflation pressure in real driving situation. Grappe et al determined the relative influence of five different levels of pressure (P) and four different levels of load (Z) on rolling resistance coefficient (C_r) and to examine the relationships of C_r with P and Z during the cycling locomotion [31]. He also concluded that this relationship is nonlinear. In fact, for the passenger cars and truck tires, the RR increases with decreasing tire inflation pressure and it also increases with the vertical load increasing. In addition, previous studies showed that vehicle speed has effect on the rolling resistance as well. The higher the speed, the more rolling resistance experienced.

It is important to understand the influence of inflation pressure on rolling resistance as the tire pressure affects the road/tire contact patch area. The load carried by the tire is dynamic, i.e. it keeps changing and is difficult to maintain a constant or optimal load, and moreover it is the inflation pressure that supports the load. The velocity at which the tire rotates does not affect the contact patch area much. In 2000, field studies carried out on road revealed that the tires of more than half of the cars were under-inflated by at least 4.5 Psi [7]. This results in a considerable increase in RR by 6% and 30%, when the inflation pressure is 4.5 Psi and 14.5 Psi below the recommended value respectively.

For any given air pressure acting on the inside of the tire and supporting a specific load, the footprint can be studied. It is important to maintain the correct inflation pressure as it affects the fuel economy of the vehicle and tire life. A Nitrogen inflated tire maintaining optimum tire pressure has a uniform contact patch area and hence the tire wears out uniformly along the contact patch. However an under inflated tire will have a lesser area of contact with the road wearing out in a non uniform manner on the outside forming a "W" pattern (See Figure 4.4).The rolling resistance also increases as the temperature at the crown increases rapidly. Similarly, an over inflated tire has non uniform wear at the center of the tire. It is very important to maintain optimum contact patch area as it also influences the braking capability of the vehicle. Figure 4.4 shows the difference in contact patch area of tires with different inflation pressures.

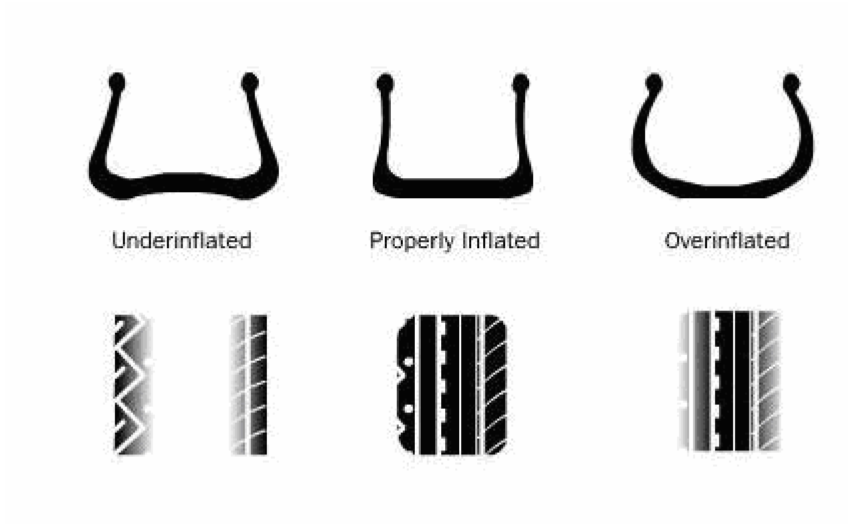

Figure 4.4: Comparison of footprint area of a tire with different inflation pressures [32].

Effect of Rolling Resistance on Fuel Economy

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% [1].

Previous testing data presented that 1.5% to 4.5% of total gasoline use could be saved if all replacement tires in use had low rolling resistance. Therefore, one of the most promising opportunities for fuel savings across the entire fleet of existing vehicles is to utilize low rolling resistance tires instead of standard replacement models. This change improves the inherent efficiency fuel over the typical 30,000 to 50,000 miles lifetime of a set of tires [33].

CHAPTER FIVE

TIRE INFLATION USING NITROGEN

Introduction

Nitrogen is a dry and inert gas which has been used to inflate aircraft, race cars, military vehicles and off-road trucks. This helps maintain the tire inflation pressure longer and improve fuel efficiency [34]. Compared to nitrogen, oxygen in compressed air permeates through the wall of the tire much faster, thus reducing the tire inflation pressure. Shop air also consists of water molecules which tend to react on the inside of the tire and corrodes the rim. Dry nitrogen can maintain the proper inflation pressure to make tires run cooler, which can decrease the rolling resistance and prevent overload.

The permeability coefficients measured for oxygen in shop air are higher than the values for nitrogen in all known rubber elastomers, including those typical of tires [35]. The ratio of the permeability coefficients of oxygen divided by that of nitrogen is between 3 and 4 depending on the particular rubber. This means oxygen permeates 3 to 4 times faster through rubber than nitrogen molecules. Size of nitrogen molecules is larger than oxygen despite the fact that the molecular weight of nitrogen (28 g/mol) is lesser than molecular weight of oxygen (32 g/mol), which might suggest that oxygen is larger than nitrogen. Moreover, water present in shop air can change from liquid to vapor form at relevant range of temperatures. At higher operating temperatures pressure in tires inflated with shop air can increase from 0.26 Psi at 60^0 F to 2.89 Psi at 140^0 F [11].

Tires degrade over time because oxygen oxidizes the rubber compounds when it migrates through the carcass of the tire, which cause under-inflation and deterioration of the rubber. Nitrogen inflation significantly reduces tire failure. Nitrogen is an inert gas, which will not corrode rims and will help the tire to run cooler [35]. Figure 5.1 shows the permeability of oxygen and nitrogen molecules through the tire.

The advantages of using nitrogen inflation in tires include: improved tire life, increase in fuel efficiency, enhanced safety of the vehicle and reduced operating cost.

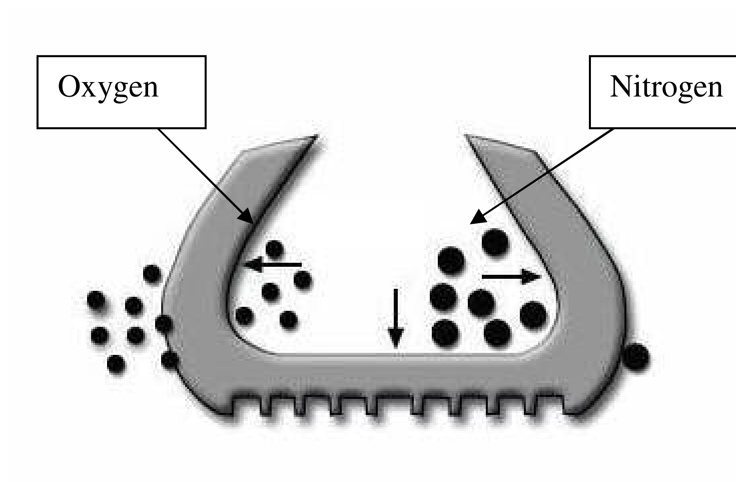

Figure 5.1: Permeability of Oxygen and Nitrogen molecules [35].

Having explained the characteristics of nitrogen gas and the advantages of nitrogen inflation on tires, the following sections will explain in detail about the tests conducted, the technique and the procedure used to test the tire with different inflation gases. A number of tires were tested with both air and nitrogen to inflate the tires and compared to see how it affects the rolling resistance of tires.

Technical Approach and Test Procedure

To begin with we propose to compare a series of mathematical models side by side and identify the most appropriate one, which will be used to predict the RR with the contribution of the physical, independent variables (i.e. load, pressure, and velocity). After that, we refine the identified model to give consideration to nitrogen tire filling. The tests conducted are split into two phases and experimental study will be performed to feed the data for calibrating the RR forecasting model. Statistical analysis is the method to determine the parameters in the model and answer the question of whether there is difference in rolling resistance due to different inflation gas. Finally, the tire performance and life as well as vehicle fuel efficiency are related to the proposed tire filling strategy through conducting statistical analysis again.

Mathematical Modeling

The coefficient of RR for pneumatic tires depends on hysteretic losses from tire deformation which is affected by the vertical force applied to the tires and the tire inflation pressure in real driving situation. The tests following the guidelines in SAE standard procedure J1269 were performed before. This test method involves testing under various load-pressure conditions (at 80kph), other than the actual test conditions. However, the trend over the recent past has been to account for the effect of the speed on rolling resistance as well. Therefore, a new test method and a new model are used to predict rolling resistance at various vehicle operation conditions (load, pressure, speed), other than the test conditions [21].

In the past, two equations have been used to model RR test data, including data at different speeds [21].

$$RR = A_0 + A_1 + A_2 \frac{L}{P} + A_3 V^2 + A_4 \frac{LV^2}{P} + A_5 \frac{1}{P} \tag{5.1}$$

$$RR = A_0 + A_1 + A_2 V + A_3 \frac{L^2}{P} + A_4 LV + A_5 V^2 \tag{5.2}$$

where L is the load acting on the tire, otherwise represented by Z.

Traditional modes as showed above provide good mathematical description of the data, but are often not very appealing from the point of physically describing the relationship between RR and the independent variables. Moreover, since this approach primarily searches for the best mathematical fit for any given data set, it results in a plethora models such that the model for each tire could have different terms. Thus, there is no common basis for comparing the models of various tires either. In view of these disadvantages, the following models were utilized in the study [21]:

$$RR = KP^{\alpha} Z^{\beta} V^{\gamma} \tag{5.3}$$

$$RR = P^{\alpha} Z^{\beta} (a + bV + cV^2) \tag{5.4}$$

where RR is the rolling resistance (N), P is inflation pressure (kPa), Z is applied vertical load (N), V is speed (kph), K is constant, α, β, γ are exponents, *a*, *b*, *c* are constant coefficients. Equations (5.3) and (5.4) are referred to as model 1 and model 2, respectively. The difference in tire pressure can be modeled from the knowledge of gas diffusion rates for both air and nitrogen inflation as:

$$P = P_{air}^{\alpha} - P_{N_2}^{\alpha} \tag{5.5}$$

Indeed, equations (5.1) and (5.2) can be derived from equation (5.3) using Taylor Series expansion and selecting only those terms that provide the best fit.

Following are some advantages of using model 1:

1. It is appealing from a physical point of view since it accounts for the effect of the three known variable; speed, pressure and load.
2. It allows the test data to determine the contribution of various terms to RR rather than selecting only those terms that result in a good mathematical fit for a given data set.
3. It is applicable for both passenger car and light truck tires.

From the SAE proposed coast down test, it was observed that the second order polynomial provided a better representation of the rolling resistance vs. speed relationship for any given load-pressure combination, this led to the development of model 2, which is better than model 1 in representing rolling resistance test data. In model 2, the correlation between calculated RR and measured values R^2 exceeds 0.99 for all those testing tires. Moreover, the residuals, which are the difference of calculated RR and measured RR, are randomly scattered. Usually, the dispersion in residual was higher for light truck tires as compared to passenger car tires. Model 2 has also the advantages mentioned before.

This new test practice J2452 over the model J1269 is that the former includes the speed dependence of rolling resistance. Hence, it is important that the parameters used for comparing tires capture their RR performance over a range of speed. However, the typical output of comparing two tires from different manufactures is a series of RR vs. speed curves. It is challenging to quantitatively compare the rolling resistance performance for two tires by only comparing their RR vs. V curves [12].

In this new test method, because the data are collected at multiple speeds for each load/pressure condition, new parameters are defined and a new methodology for comparing tires using data generated as per SAE J2452. The new parameters are MERF (Mean Equivalent Rolling Force) and SMERF (Standard Mean Equivalent Rolling Force).

MERF for a tire, at a given load/pressure condition, is defined as the average of all rolling resistance values corresponding to every single speed-time point in a fixed driving cycle. Mathematically, MERF is defined as [22]:

$$MERF_{U/H} = \frac{\int_{t_o}^{t_f} RR dt}{\int_{t_o}^{t_f} dt} = \frac{P^{\alpha} Z^{\beta} \left[\int_{t_0}^{t_f} (a + bV + cV^2) dt \right]}{\int_{to}^{t_f} dt} \tag{5.6}$$

where $MERF_{U/H}$ is the mean equivalent rolling force over any standard urban (U) or highway (H) cycle. The term t_o is the time corresponding to the start of the cycle and t_f corresponds to the end of the cycle.

Since $RR = f(V)$ and $V = f(t)$ for a giving driving cycle is known, 'V' in equation (5.6) can be expressed as a function of time. Hence, the integral can be solved by standard numerical integration methods, and equation (5.6) can be simplified to:

$$MERF_{U/H} = \frac{P^{\alpha} Z^{\beta} \left\{ at_f + b\sum_{i=1}^{f} (t_i - t_{i-1})(V_i - V_{i-1}) + c\sum_{i=1}^{f} (t_i - t_{i-1})(V_i^2 - V_{i-1}^2) \right\}}{t_f - t_o} \quad (5.7)$$

Selecting a unit time interval ($\Delta t = t_i - t_{i-1} = 1\sec$) between successive speed points on the speed vs. time curve for a driving cycle

$$MERF_{U/H} = \frac{P^{\alpha} Z^{\beta} \left\{ at_f + b\sum_{i=1}^{f} V + c\sum_{i=1}^{f} V^2 \right\}}{t_f - t_o} \quad (5.8)$$

where t_f now represents the duration of the cycle because t_o =0.

It is noted that equation (5.8) can be used to calculate the MERF for any cycle. At a given load/pressure, the final MERF for a tire is a weighted average of the EPA urban and highway cycles.

$$MERF = 0.55(MERF_U) + 0.45(MERF_H) \quad (5.9)$$

SMERF for any tire is the MERF for that tire under standard load/pressure conditions defined in SAE J2452.

MERF values for two tires at a given load/pressure condition can be directly compared, where a lower value is better. One of the advantages of using MERF is that for one tire to be better than others, it would have to be better over a range of speeds.

However, the limitation of the methodology J2452 should be kept in mind:

1. Stabilizing the tire at some speed other than 80 kph does not have a significant effect on the speed dependence.
2. No other phenomenon, such as standing waves, contributes to the tire rolling resistance. There is some work recommended to be done in the future.
3. A more precise estimate of the standard deviation of the distribution of MERFs (σ_{MERF}) should be obtained using a larger variety of tires.
4. The error in the measurement of RR during a stepwise coast down test should be experimentally determined to obtain a more accurate estimate for σ_{MERF}.

Experimental Study

The research detailed in this report focuses on how nitrogen filled tires can help improve fuel economy and increase tire life by studying the effect of parameters such as

Load (*L*), inflation pressure (*P*) and speed (*V*). In order to achieve the objective, a number of tests were done on different tires and the obtained results were analyzed. Now that we know the mathematical model to be implemented in analyzing the results, the tests were conducted in two steps.

Phase 1 of the testing was done to study the tire inflation gas leakage at different test temperature and time frame. The tests conducted include Qleak and Sleak tests performed by MARC (Michelin America Research Cooperation) on a number of passenger car and light truck tires. Qleak test is conducted to asses the pressure drop in tires with nitrogen and dry air inflation at room temperature ($21^\circ C$) for about 16 to 17.7 days. Similarly Sleak test helps asses pressure drop in the tires at a higher temperatures ($30^\circ C - 35^\circ C$) for a time period of about 28 days. The drop in inflation pressure of the test tires is noted at equal intervals and rolling resistance is calculated for the inflation pressure at the start and end of each experimental cycle for each tire. The values of load (*Z*) and velocity (*V*) were considered to be constant values so that the tires could be hypothetically analyzed for only the effect of inflation pressure on rolling resistance. Although the rolling resistance values were not calculated under real driving conditions, it could show the pressure leakage rate for both inflation types and also the predicted rolling resistance values corresponding to pressure readings. Al the tests were performed in static state.

While studies conducted in Phase 1 are static, Phase 2 mainly focuses on determining the influence of tire inflation pressure on rolling resistance under dynamic rolling conditions. In the second phase of testing, different tires inflated with shop air and nitrogen were tested on Wal-Mart tractors and the data were used for analysis. A number of tractors were tested at different locations and the inflation pressure and tire tread depth were recorded at regular intervals to study the inflation gas leakage at different time frame. The absolute values of rolling resistance of the tires were calculated and tabulated to show decrease in rolling resistance with increase in tire pressure and how this, in turn, increases the fuel economy of the vehicle.

In Phase 2, the effect of inflation pressure and axial load are considered while the velocity is taken to be a constant value. This is because the tires are filled with both nitrogen and air to calculate the pressure drop at regular intervals of time, at the same operating conditions to calculate rolling resistance, fuel economy and tire tread wear. Figure 5.2 shows the experimental data requirement including the data range and data format for this project. The format of the final results is also presented below.

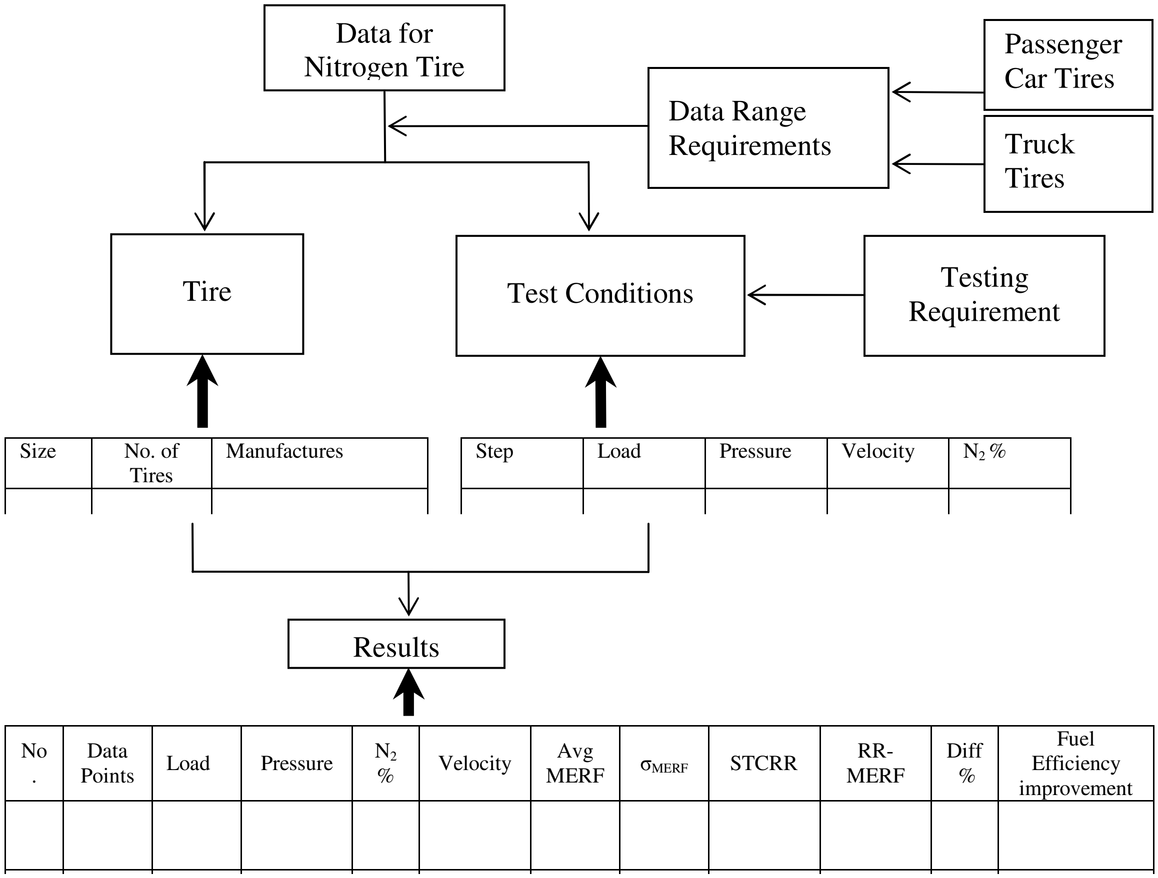

Figure 5.2: Procedure and approach.

Since this study will be performed over a range of inflation pressure values for given speed and load rating, the recommended range for each parameter should be described. Table 5.1 shows the proposed test rage for the experimental parameters.

Table 5.1: Proposed test range

PARAMETERS	RANGE
Air Pressure	Normal±80kPa
Load	0% of Max to 100% of Max
Speed	60mph to 150mph
N_2 Pressure	0% to 100% Total inflation

Figure 5.3 proposes the general procedure to be followed while conducting the tests on tires. Tests in Phase 1 were based on the described procedure while for Phase 2 the same mathematical model was chosen and fuel economy and tire life were directly calculated from the measured rolling resistance values. The test results were compared side by side for both inflation types to support the statement that nitrogen inflation can improve fuel efficiency and tire life.

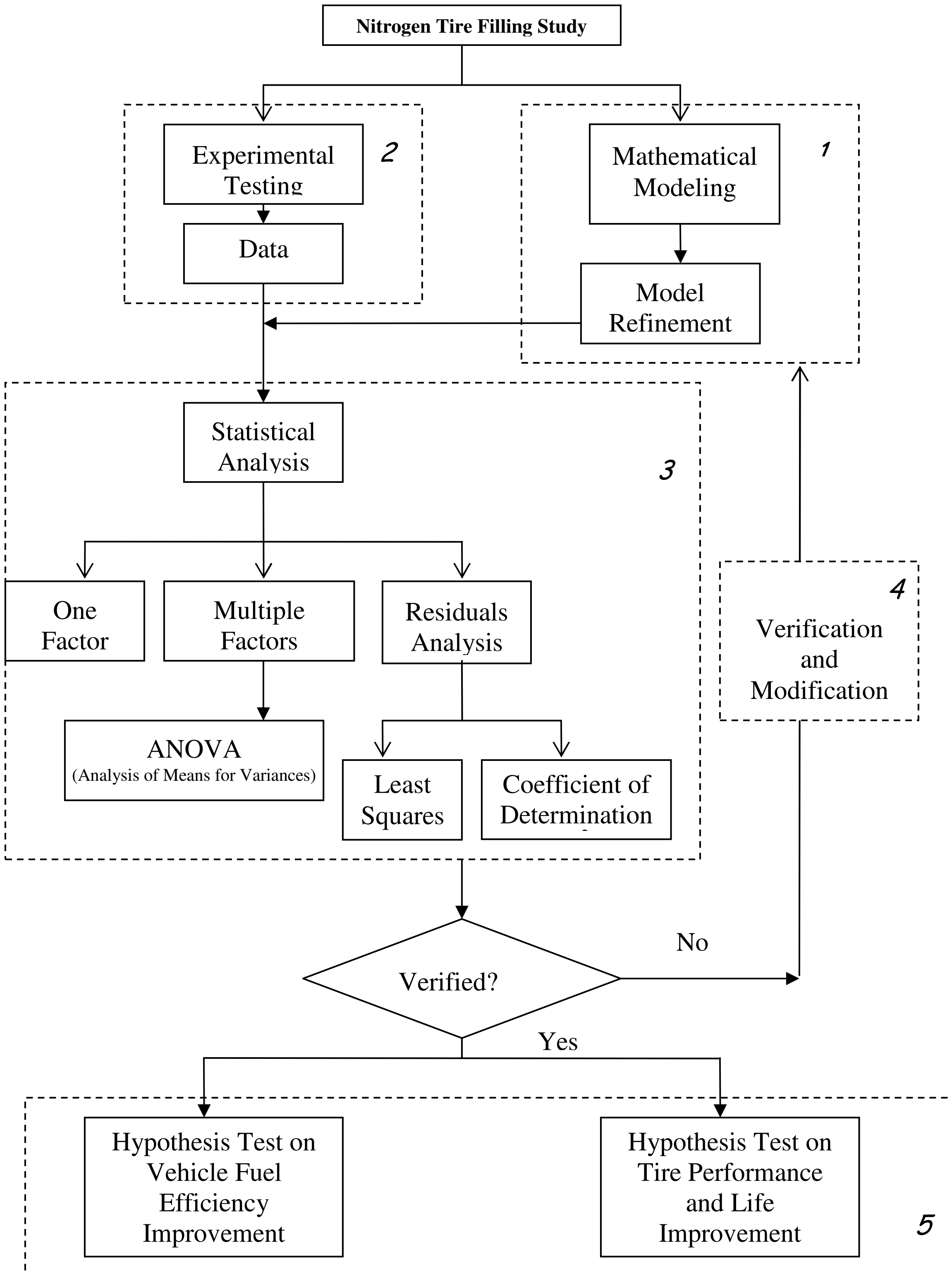

Figure 5.3: Technical procedure flowchart

As shown in Figure 5.3, statistical analysis was conducted in both modules 4 and 5 using available statistical tools (e.g., Statistical Analysis Software and Microsoft Excel).

The methods involved in module 4 include Single Parameter Effect, Multiple Factor Interaction and Residual Analysis. One-factor interaction analysis focuses on finding how each parameter affects Rolling Resistance. Multiple Factor Interaction focuses on interaction between different factors. It can be performed by Analysis of Means (ANOM) and Analysis of Means of Variance (ANOMV). Residual analysis on the other hand can be used to check errors and show the correlations. This can be performed by Least Squares and coefficient of determinations.

Module 5 was completed by calculating the rolling resistance and tire tread wear from the data collected from Wal-Mart truck tires. Equation (5.3) was used to calculate the rolling resistance of truck tires filled with both air and nitrogen and compared side by side to study the effect of inflation pressure on the rolling resistance of tires. All the data collected from Wal-Mart trucks were tabulated to first find the leakage rate of inflation pressure for both inflation types. The tread depth of tires for both inflation types were periodically recorded for the corresponding pressure reading. Based on this, the rate of wear of tire tread was calculated.

Phase One Tire Testing

Testing and Analysis:

As mentioned earlier, the two tests namely Qleak and Sleak tests were conducted on test tires to check the gas permeation in both air and nitrogen inflated tires. While Qleak tests were conducted during certain days in room temperature, Sleak were performed at higher temperatures. All these tests were performed in static state. A testing period of 17.7 days (or 18 days) and 28 days were used for Qleak and Sleak tests respectively. The start/end pressure varies according to different tire type. The tires were first heated up at the beginning of the testing and cooled down in 4 hours at the end. Test pressure was 5.5 bar (80 Psi) for Sleak tests.

In order to obtain the constants used in the model, nonlinear regression techniques can be used. Nonlinear technique that iteratively arrives at a solution by minimizing the sum of the square of errors (SSE) was applied to obtain the parameters for the regression model. This can be easily accomplished using a spreadsheet that includes an inbuilt routine for solving iterative problems. How the inflation pressure changed with time in different environmental temperature was studied. All these tests were performed at MARC.

Four tires, each with the dimensions shown in Table 5.2 corresponding to various categories, were tested at 4 different laboratories for both Qleak and Sleak tests. Two tires were inflated with nitrogen (95% purity) and the other two similar tires were inflated with dry shop air in each test.

Table 5.2: Tire serial numbers, inflation type and size

TEST		TIRE SERIAL NO.	INFLATION TYPE	TIRE SIZE
QLEAK	SLEAK			
Test 148913	Test 148916	93066627	Nitrogen	LT265/65R18122/119R (Rugged Jeep Tire)
		93066688	Nitrogen	
		93066689	Dry air	
		93066696	Dry air	
	Test 148918	A09L	Nitrogen	T125/70D15 MINI SPARE 95M (Spare Tire)
		CIR0	Nitrogen	
		A04L	Dry air	
		A01R	Dry air	
Test 148914	Test 148917	56900048	Nitrogen	P235/55R17 98VTLEN (Passenger Car)
		56900049	Nitrogen	
		56900051	Dry air	
		56900052	Dry air	
Test 148919	Test 148921	37504265	Nitrogen	445/50R22.5 XONEXDAHT+TL (Truck Tire-Front)
		37504267	Nitrogen	
		37504072	Dry air	
		37504074	Dry air	
Test 148920	Test 148922	33104382	Dry air	275/80 R22.5 PILOT XZE TL LRG (Truck Tire-Trailer)
		33104383	Dry air	
		33104386	Dry air	
		33104388	Dry air	

Qleak Test Results and Discussions:

All the recorded data points of inflation pressure drop were plotted versus the corresponding time in days for a number of tires with both the inflation gases. The type of test done, inflation gas and tire type can be obtained from Table 5.2 to interpret the result obtained. All the results are shown in the following figures and Tables. Figure 5.4 through 5.7 show pressure change with time in Qleak test.

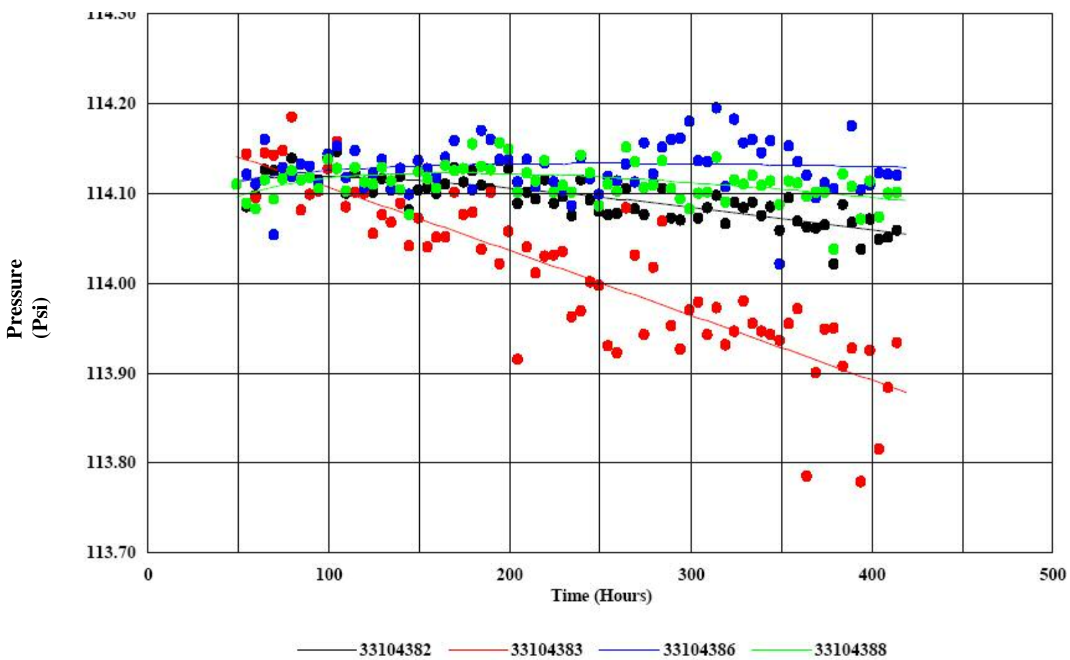

Figure 5.4: Measured inflation pressure change with time in Qleak test for 275/80 R22.5 PILOT XZE TL LRG [36]

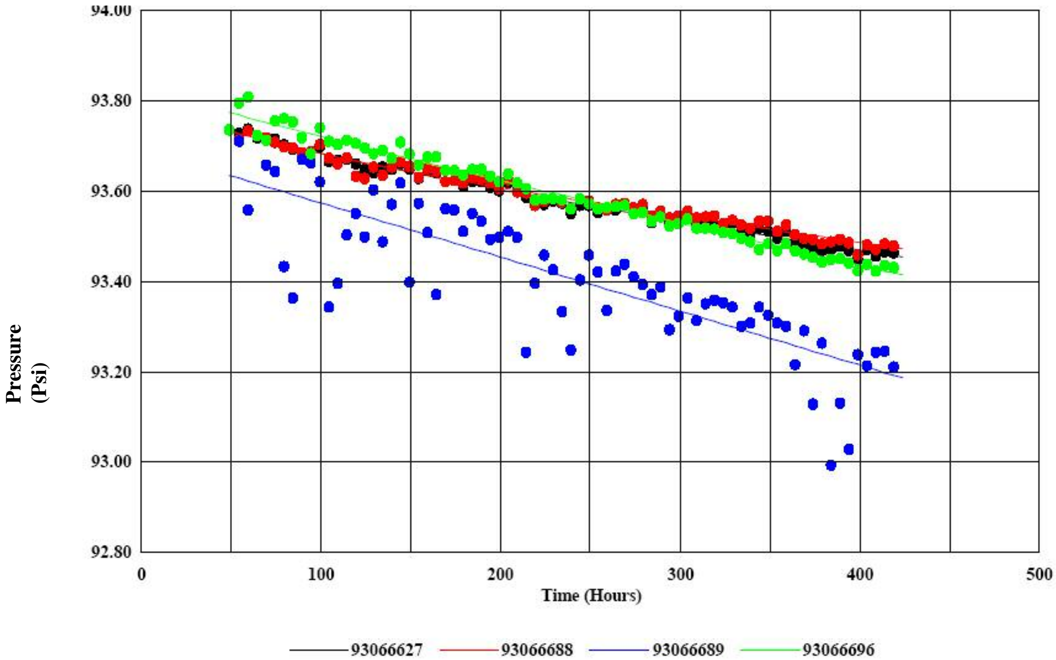

Figure 5.5: Measured inflation pressure change with time in Qleak test for LT265/65R18122/119R [36]

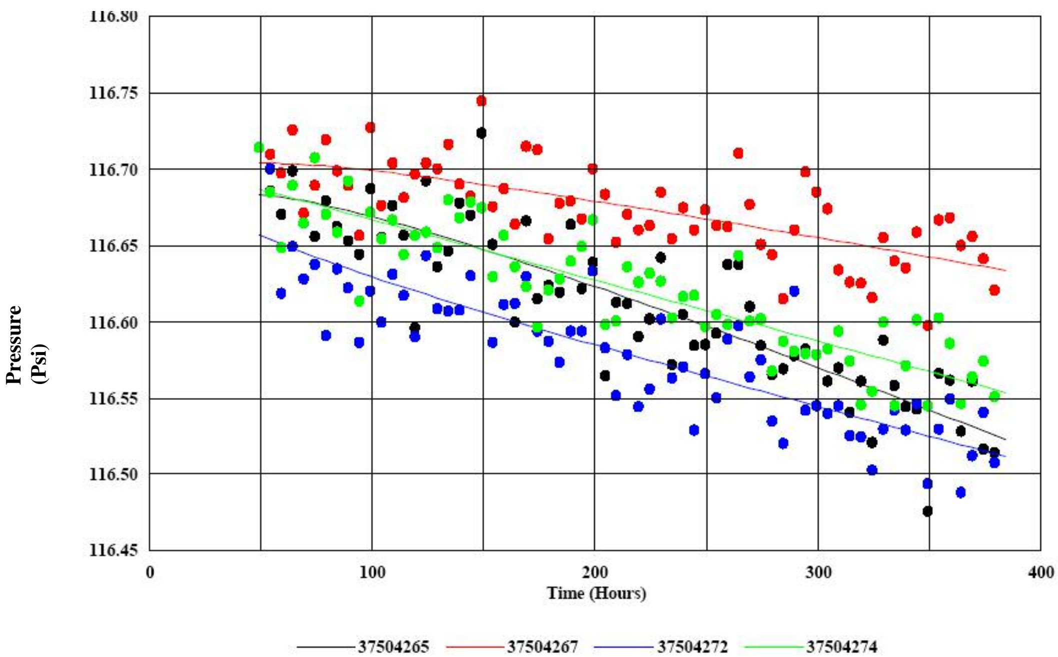

Figure 5.6: Measured inflation pressure change with time in Qleak test for T125/70D15 MINI SPARE 95M [36]

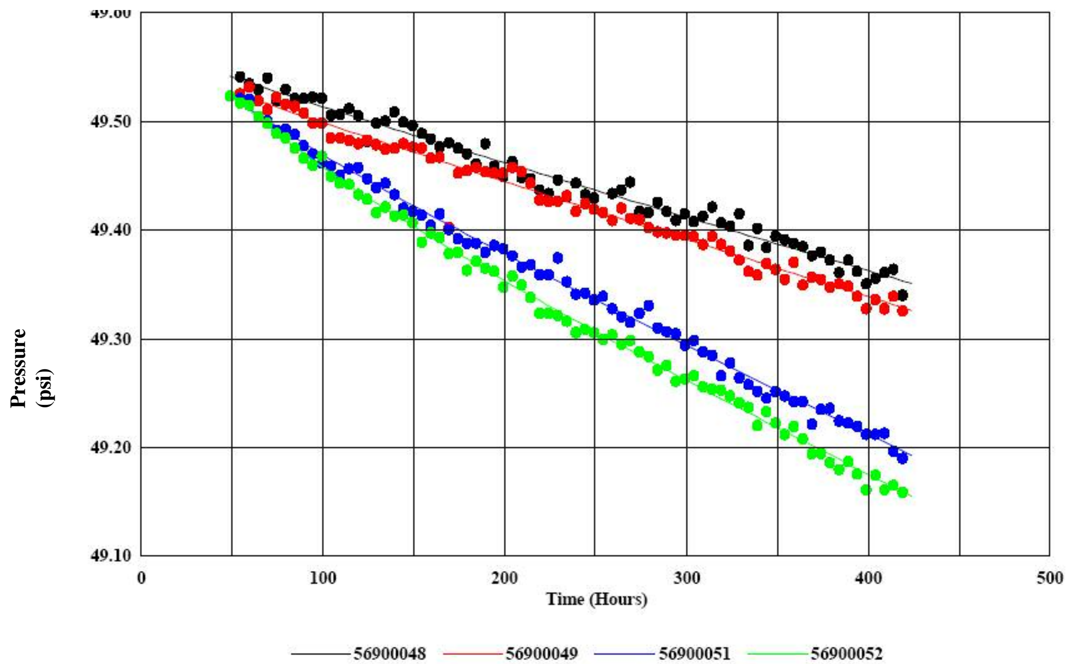

Figure 5.7: Measured inflation pressure change with time in Qleak test for P235/55R1798VTLEN [36]

Figure 5.4 shows the pressure readings on a truck tire where all the four tires are filled with shop air only. They don't follow any particular pattern and is scattered all over. However, for tire with serial number 33104383, the pressure drop over time is predominant. Figure 5.5 and 5.6 show a slightly greater decrease in inflation pressure of air inflated tires compared to nitrogen tires whereas Figure 5.7 clearly shows the pressure drop for both inflation types for passenger cars over same period of time. Qleak tests do not clearly indicate a greater permeability of air filled tires over that of nitrogen filled tires because the test is conducted at room temperature and this does not represent real driving conditions.

As seen from Figures 5.4 through 5.7, for nitrogen inflation and air inflation in 4 different tires, the measured pressure decreased almost linearly as time passes by. It was observed that the current model provide a better representation of the inflation pressure vs. time relationship with any given tire types. However, the error was larger for one tire compared to the other three. This requires further analysis and study.

The data points picked out from the graphs shown (Figure 5.4 to Figure 5.7) are analyzed to calculate the percentage of inflation gas leakage and standard error per month for the corresponding tire serial numbers as shown in Table 5.3 to 5.6. The tables are a direct interpretation and comply with the results shown already. In Tables 5.3 to 5.6, the letter 'A' suffixed to the tire serial number represent air inflation and the letter 'N' represent nitrogen inflation in the tires. It clearly shows that permeability of nitrogen molecules is higher than that of oxygen molecules even at room temperature.

Table 5.3: Gas leakage in Qleak test for 275/80 R22.5 PILOT XZE TL LRG [36]

Serial Number	Gas Leakage in % per Month	Standard Error in % per Month
33104382-A	0.24%	0.05%
33104383-A	0.53%	0.13%
33104386-A	0.07%	0.08%
33104388-A	0.22%	0.05%

Table 5.4: Gas leakage in Qleak test for LT265/65R18122/119R [36]

Serial Number	Gas Leakage in % per Month	Standard Error in % per Month
93066627-N	0.48%	0.04%
93066688-N	0.43%	0.04%
93066689-A	1.08%	0.31%
93066696-A	0.82%	0.05%

Table 5.5: Gas leakage in Qleak test for T125/70D15 MINI SPARE 95M [36]

Serial Number	Gas Leakage in % per Month	Standard Error in % per Month
37504265-N	0.45%	0.09%
37504267-N	0.21%	0.07%
37504272-A	0.24%	0.09%
37504274-A	0.28%	0.07%

Table 5.6: Gas leakage in Qleak test for P235/55R17 98VTLEN [36]

Serial Number	Gas Leakage in % per Month	Standard Error in % per Month
56900048-N	0.99%	0.07%
56900049-N	1.07%	0.08%
56900051-A	1.51%	0.05%
56900052-A	1.48%	0.05%

Sleak Test Results and Discussions:

Sleak tests were performed on test tires similar to the Qleak test except that it is conducted at controlled higher temperatures in an oven. The pressure drop in tires with both inflation types is clearly visible in Sleak test and is better than Qleak test. This is because at higher temperatures, the energy of the inflation gas molecules increase leading to increased pressure and permeability.

The permeability of air in tires at higher temperatures is greater because air contains moisture. Water is usually present in the case of conventional compressed air. At lower temperatures, as a liquid, water occupies very little volume. However, as temperature increases, liquid water vaporizes to become a gas and its volume expands, causing total pressure to be higher in the tire, than would be the case with dry gas. Thus, the presence of water in a tire contributes to pressure variations as temperatures change [11]. However the change in pressure of both the inflation gases would be in a similar pattern if air used for inflation is dry.

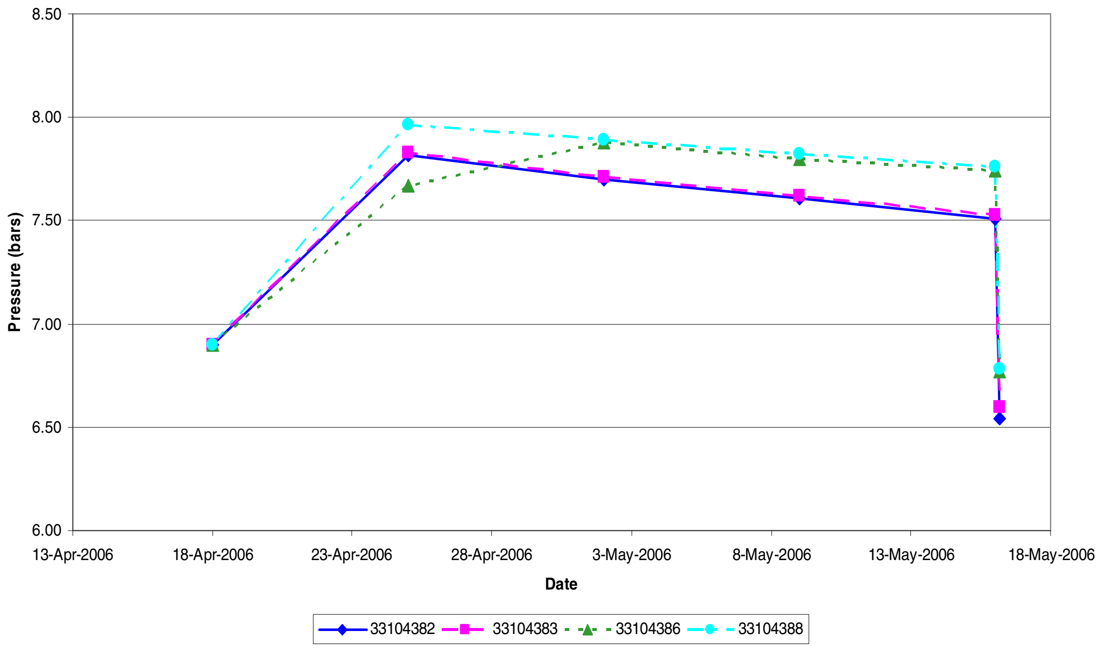

Figure 5.8: Measured inflation pressure change with time in Sleak test for 275/80 R22.5 PILOT XZE TL LRG [36]

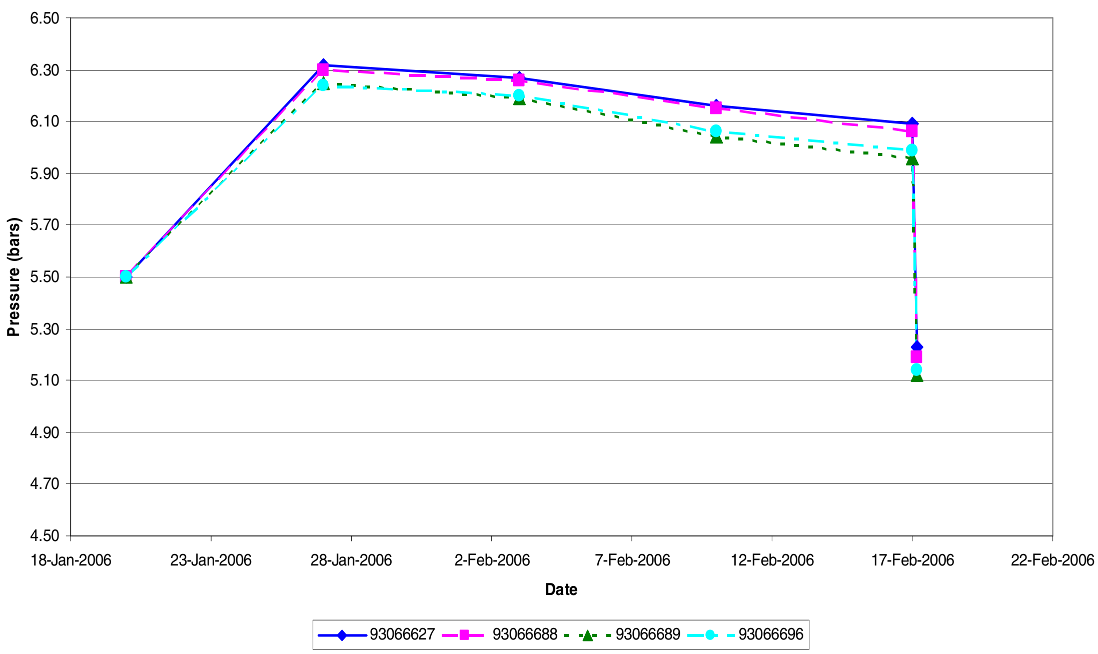

Figure 5.9: Measured inflation pressure change with time in Sleak test for LT265/65R18122/119R [36]

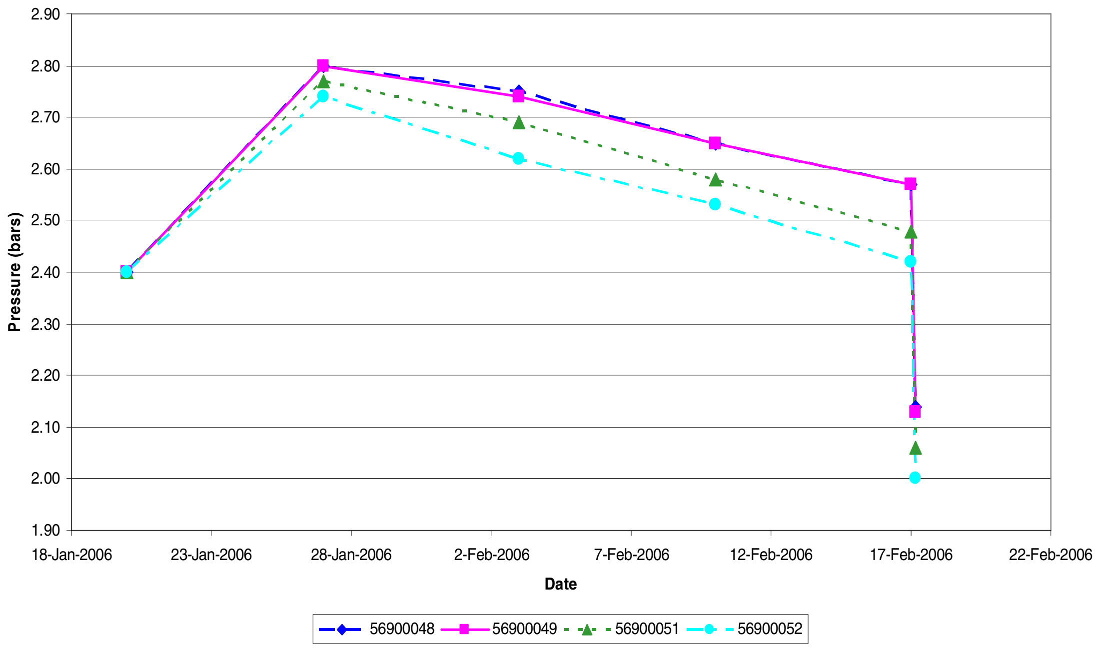

Figure 5.10: Measured inflation pressure change with time in Sleak test for P235/55R17 98VTLEN [36]

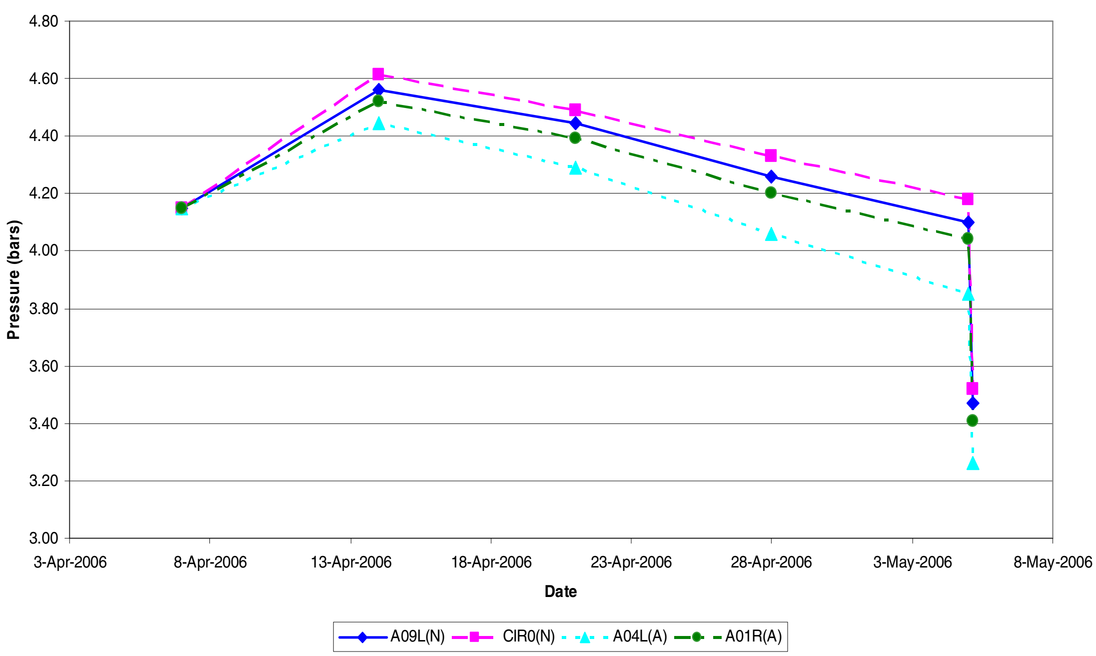

Figure 5.11: Measured inflation pressure change with time in Sleak test for T125/70D15 MINI SPARE 95M [36]

As seen from the results of the Sleak tests from Figure 5.8 to Figure 5.11, the inflation pressure of the tires with both inflation types initially go up in the first week. This is because of the increase in energy of the gas molecules in the tire. Then they start going down similar to the Qleak test as the increase in energy induces gas leakage as time passes. Due to smaller size of air molecules compared to that of nitrogen, air leaks faster in tires. After 4 hours cool down at the end of the test, the tire pressure goes down straight to a lower value than at the beginning of the test. This is a clear indication than gas has leaked out of the tire during the test. The experimental study showed that the nitrogen inflation can maintain the tire pressure 29% to 35% better than shop air per month in oven temperature depending on different tire type.

Although Qleak and Sleak tests show that nitrogen can retain inflation pressure better than shop air, it is only a static test conducted in a laboratory environment. It is necessary to further investigate the behavior of both inflation types under real driving conditions where readings are taken after each driving cycle. The results obtained from tests conducted on Wal-Mart truck tires for real driving cycles at different locations representing different driving conditions will be discussed in the phase two of the project which is to follow.

Phase Two Tire Testing

Testing and Analysis:

In Phase 2 of the project, Wal-Mart truck fleets in 3 locations namely; Sealy, Texas; Mt. Crawford, Virginia and Bentonville, Arkansas were filled with both nitrogen and air and the inflation pressure and tread depth of all the 10 tires of each truck were recorded periodically to investigate inflation pressure leakage at different time frames. The absolute values of rolling resistance of the tires are calculated and tabulated to investigate the increase in rolling resistance with decreasing tire pressure and how this affects the fuel economy of the vehicle and its tire performance.

Each truck at a specific location was filled with one of the inflation gases and readings were recorded at the end of every 2 weeks. The trucks carried an average load of 80,000 lbs and travel about 2500 miles per week. Every time a pressure reading is noted, the tread depth of each tire of each truck corresponding to the inflation pressure is also recorded. The tread depth is noted at 3 places of each tire once every two weeks. The inflation pressure of each tire is noted in terms of kPa and tire depth in terms of millimeter. Mileage readings of the truck were also noted to calculate the life of each tire and its inflation pressure leakage rate depending on the distance covered by tire per week.

There are two different types of tires, namely Michelin and Bridgestone tires, under study. Since we are interested in finding the influence of inflation pressure on rolling resistance, the parameters such as load (Z) and velocity (V) are considered constants throughout the test. In fact, the regression exponents used for both the tires are considered to be the same as it is determined that for truck tires the value of α and β are respectively -0.2 and 0.9 (obtained from MARC).

Since the rolling resistance force F_r is proportional to the normal force acting on the tire, it is natural to define the coefficient of rolling resistance C_r as:

$$F_r = (C_r)(Z) \tag{5.10}$$

where C_r is the coefficient of rolling force and Z is the normal load acting on the tire at its axis of rotation.

The normal coefficient of rolling resistance for trucks is about 5kgf/T (obtained from MARC). Substituting this into Equation (5.10) yields the normal rolling force of truck tires to be about 98.851 N per wheel when considering the overall truck load to be 80,000 lbs, i.e., 4444.44 lbs/wheel. To determine the influence of Load (*Z*), Velocity (*V*) and Pressure (*P*) on rolling resistance, we consider equation (5.4) to be the RR equation.

Since only absolute values of rolling resistance are found, we neglect the effect of velocity. Hence values of normal load and the velocity terms are considered to be constant for both tires types.

Now, Equation (5.4) becomes,

$$F_r = P^{\alpha} Z^{\beta} k \tag{5.11}$$

By selecting a value of inflation pressure, the value of constant (k) is determined to be 0.182 / Pa. All the calculations were done by using this constant (K) value of 0.182 per Pa and substituting inflation pressure in Equation (5.11) to determine the corresponding rolling resistance values.

All the tires in all the 3 locations along with their corresponding sizes, the vehicle model and the inflation types are represented in Table 5.7. The tire sizes, model and serial numbers of each of the ten tires of each truck were systematically recorded to calculate the rolling resistance of each tire.

Table 5.7: Location, tire size and inflation type

Location	Vehicle Model	Tire Make	Tire Size	Inflation Type
Sealy	9400 i	Michelin	275/80R22.5	Air
				Nitrogen
Mt. Crawford	Class 8	Bridgestone	295/75R22.5	Air
				Nitrogen
Bentonville	9400 i	Michelin	275/80R22.5	Air
				Nitrogen

Rolling Resistance Test Results and Discussions:

All the tests were conducted on Wal-Mart tractor trailers with 18 wheels each. Each of these trucks in a specific location was filled with a different inflation gas, and pressure and tread reading were noted every 2 weeks. The reading were noted down by the drivers and input into the database using PDA. All the data recorded were then processed to systematically segregate the data for every truck at a given location. The absolute value of rolling resistance of the trucks for its corresponding values of inflation pressure at all the locations is given in Table 5.8. The rolling resistance values were tabulated based on the readings noted at the end of a testing cycle of one month for the month of December 2006 and January 2007.

Table 5.8: Rolling resistance comparison at each Location

Location	Filling Type	Starting Pressure (kPa)	Ending Pressure (kPa)	RRs (N)	RRe (N)	Increment (N)	Percentage Difference (%)
Sealy	Nitrogen	517	505	96.34	96.79	0.45	71.7
	Air	585	538	93.98	95.57	1.59	
Mt. Crawford	Nitrogen	667	655	91.55	91.88	0.33	70
	Air	688	648	90.98	92.08	1.1	
Bentonville	Nitrogen	556	545	94.94	95.32	0.38	69.6
	Air	606	567	93.32	94.57	1.25	

Based on the test data, rolling resistance statistics were calculated using different inflation pressures at the beginning and end of each test run, while keeping other parameters constant. As seen from Table 5.8, the nitrogen filled tires have at least 70% lesser rolling resistance compared to air filled tires due to their capability to maintain the inflation pressure longer. To further understand the leakage rate of nitrogen and air in the truck tires, the pressure drop per mile of both tires were calculated. Considering that a truck travels about 2500 miles/week, Table 5.9 represents pressure drop per week at each location based on inflation pressure value at start and end of each run and the mileage readings for the corresponding pressure vale of every test cycle.

Table 5.9: Inflation pressure drop per week at each Location

Filling Type	Inflation Pressure drop/week (kPa)		
	Sealy	Mt. Crawford	Bentonville
Nitrogen	3.0	2.9	2.9
Air	11.8	10.2	9.8

The inflation pressure drop values in Table 5.9 were based on the truck mileage readings only and they match with the inflation pressure results in Table 4.8. These results show how tire inflation pressure plays an important role in rolling resistance of tires. Since contact patch area of a tire is a direct function of its inflation pressure, with decrease in inflation pressure, contact patch area increases, hence more energy is expelled in moving the tire, increasing the rolling resistance. Lower inflation pressure causes the premature and irregular tire wear as more tire area comes in contact with the road during rolling. The influence of tire pressure on tire life is explained in the following section.

Tire Tread Wear Results and Discussions:

Measuring the inflation pressure drop in truck tires filled with air and nitrogen are not limited to only evaluating the rolling force at the road/tire interface. It is important to investigate its importance on tire life too because especially for 18 wheeled tractor trailers, improving the tire life of every tire plays a very important role in the overall cost spent on replacement tires every year. If improving tire life of every truck is important then its impact on enterprises with a large fleet of trucks is enormous.

Truck tires are replaced at periodic intervals based on the number of miles they run and the tire tread depth. Typically the front truck tire is replaced every 130,000 miles when the tire tread depth reaches 6/32 nds of an inch (4.7 mm). The rear tires are replaced every 250,000 miles when the tread depth reaches 4/32 nds of an inch (3.2 mm). Based on these Figures and the tread depth measurements on the truck tires corresponding to the mileage readings, the extra miles a tire would run in nitrogen inflated tires have been calculated. The improved tire life is because of the smaller, optimum contact patch area a nitrogen inflated tire can maintain for a longer time.

Tables 5.10 and 5.11 describe the wear rate of front and rear tires of a truck for both inflation types. The wear rates are based on the tire wear per mile traveled. Tables 5.10 and 5.11 show that the life span of front tires of a truck on an average can be increased by 48% and rear tires of a truck can be increased by 51%. This is, however, the average value of all the venues together, individual wear rates also shows that nitrogen inflated tires have a positive impact. This helps increase the mileage of tires thus reducing the cost of replacement tires.

Table 5.10: Rate of tread wear of front tires per mile.

	Nitrogen Inflation	Air Inflation		
Location	Wear/mile (mm)	Wear/mile (mm)	Increment (mm)	Percentage (%)
Sealy	0.00005082	0.0001	0.000049	49
Mt. Crawford	0.000068	0.00013	0.000062	48
Bentonville	0.000052	0.0001	0.000048	48

Table 5.11: Rate of tread wear of rear tires per mile.

	Nitrogen Inflation	Air Inflation		
Location	Wear/mile (mm)	Wear/mile (mm)	Increment (mm)	Percentage (%)
Sealy	0.000071	0.00015	0.000079	53
Mt. Crawford	0.000081	0.00016	0.000079	49
Bentonville	0.00006	0.00012	0.00006	50

Tables 5.10 and 5.11 only give the increase in tire life in percentage. In order to better understand the effect of nitrogen inflation tire life, Table 5.12 shows the tire life in terms of miles it can run before they need to be changed. It can be observed that on an average, the front tires can at least run an additional 62833 miles and the rear tire can run 126667 miles. This better explains the potential cost cut on replacement tires for every truck with 18 wheels each.

Table 5.12: Mileage increase of nitrogen inflated tires

	Front tire			Rear tire		
	Air inflation	Nitrogen inflation	Increment	Air inflation	Nitrogen inflation	Increment
Location	Mileage (miles)	Mileage (miles)	Mileage (miles)	Mileage (miles)	Mileage (miles)	Mileage (miles)
Sealy	130,000	193,700	63,700	250,000	382,500	132,500
Mt. Crawford	130,000	192,400	62,400	250,000	372,500	122,500
Bentonville	130,000	192,400	62,400	250,000	375,000	125,000

Fuel Economy and Environmental Effects:

Past research shows that for every 3% reduction in rolling resistance, fuel economy can be improved by 1% [6]. Hence, it is important to improve fuel efficiency of trucks as it would drastically cut down the money spent on fuel. The above results show that by using nitrogen inflated tires, the rolling resistance can be decreased by about 70%. Hence, for a reduction of 70% rolling resistance in tires, fuel economy can be improved by 23%.

Let us consider that a truck using air inflated tires, on an average, gives a mileage of 7 miles per gallon. Then the mileage of a truck using nitrogen inflated tires would increase to 8.6 miles per gallon due to 23% improvement in fuel economy. A truck traveling 2500 miles per week would use up only 290 gallons of fuel running on nitrogen inflated tires when compared to 357 gallons of fuel for a truck using air inflated tires. Hence one can save about 67 gallons of diesel every week by using nitrogen inflated tires. This is about 270 gallons of fuel savings every month and about 3240 gallons of diesel every year. Considering the cost of diesel to be $2.8/gallon as per government norms in May 2007, one can save $756 per month per truck and $9072 per truck per year. For a fleet consisting of 150 trucks, cost savings on fuel is $1,360,800 per year.

Improving fuel economy by decreasing rolling resistance also has a positive impact on the environment. We can save 3240 gallons of fuel every year which means CO_2 emission due to burning 3240 gallons of diesel into the atmosphere is prevented. As presented by EPA, burning 1 gallon of diesel emits 10.1 kg of carbon dioxide into the atmosphere. By saving 3240 gallons of diesel we can reduce CO_2 emissions by 32.7 tones every year per truck. Hence for a fleet of 150 trucks CO_2 emission can be reduced by 4,905 tones every year by using nitrogen inflated tires.

All the above results obtained are in agreement with the objective of this research. These results suggest that nitrogen inflation has a positive effect on the truck as well as the economy. This helps improve passenger safety and fuel economy of the vehicle. In the long run one can notice a reduction in the amount of money spent on fuel and tires. The impact of nitrogen inflation on fuel efficiency plays a very important as gasoline and diesel is non-renewable resources of energy. If using nitrogen gas to inflate tires can reduce CO_2 and fuel consumption of vehicle then they seem to find a very meaningful purpose in today's economy.

CHAPTER SIX

FINITE ELEMENT TIRE MODELING AND ANALYSIS

Introduction

It is important to understand the behavior of tires with various inflation pressure and loading conditions to predict the forces acting at the road/tire interface. In this research, a finite element model (FEM) of the 275/80R22.5 tire was developed using ABAQUS which would serve to give an insight of the approach used to experimentally predict the rolling resistance of truck tires. All the research works done in the past to predict tire behavior using FEM was based on loading the tire statically and dynamically to calculate the tire forces for different operating conditions. The analysis attempted in this work is based on similar approach. A 3D model of the aforementioned truck tire was first developed and inflation and static loads were applied to study the tire forces developed at the contact patch. This developed FEM of the tire can be used to conduct a large number of analyses including dynamic rolling, slip and friction analysis, tire burst [33] and temperature prediction of rolling tires [21] with required input variables.

The tire, wheel and various other parts that go into tire modeling were modeled with the geometry to be as close to a real tire as possible. However, due to insufficiency in various input data such as exact geometry and material properties the analysis results cannot exactly match the experimental ones. This finite element analysis could nevertheless prove to be very useful in viewing certain details that cannot be otherwise noticeable in experimental testing techniques. Based on this finite element analysis that would be explained in the following sections, future tire models can be developed and analyzed which can predict results that can be handy in designing experiments or even improve the current models.

Tire Modeling

The tire model was created using different materials and their properties for each and every material that goes into tire construction. The ability of the tire to withstand load is primarily due to a number of different materials that are usually embedded in the tire to give it stiffness and strength. The tire was first given a specific shape based on its configuration value of 275/80R22.5 and this was assigned to be made up of rubber. Later, other parts were individually modeled and meshed using different techniques and tied together. In ABAQUS, all the parts can be embedded into the base tire model using embedded element technique which helps model the tire as one single part with different material properties. However, this increases the computational time if the tire is directly modeled as a full 3D model. Hence, the individual parts were separately created and the nodes were tied together using tie constraints. This 3D model is then mounted on a rim and inflated with inflation pressure and then loaded against a rigid road model to carry out various analyses.

The entire tire model consisted of the following parts:

1. Tread and Sidewall
2. Nylon Plies
3. Polyester Plies
4. Steel Plies

5. Steel Bead
6. Rigid Wheel Assembly
7. Rigid Road

Since rubber is essentially a hyperelastic material, it produces large deflection for even considerably smaller loads. Hence, rubber material alone does not have the capability to withstand high load. Typically, nylon’s high strength is required to provide strength to tire carcass and while polyester’s high elastic modulus and low elongation reduce tire deflection under service conditions. They also give the tire a robust fit to the wheel during inflation and loading. The steel plies are placed just under the tire tread region to improve the strength of the tire to withstand axial loading. In truck and off-road tires, these plies are thicker and stronger based on their application and operating terrain. The steel beads are embedded at the sides of the tire where it comes in contact with the rim. The steel beads give the tire the strength to hold onto the rim when the tire is filled with inflation gas and also during rolling conditions.

From the above list of materials, nylon and polyester were single plies whereas steel plies consisted of two plies oriented at an angle of +20 and -20 degrees, respectively. The polyester ply was oriented at an angle of about 90 degrees to represent a radial tire. It is important to give the belt cord orientation since any change in the belt cord angle can increase or decrease the tire stresses and strains at the contact patch [5] as it influences the stiffness of the tire. The various plies are modeled as rebar materials using ABAQUS which models it as reinforcing materials in the tire. The plies are also given material orientation specific to a coordinate system and defined the direction of normal. Table 6.1 gives the geometric properties of the rebar reinforcement materials used in this simulation.

Table 6.1: Geometric properties of the rebar reinforcement materials

Material	Cross Sectional Area (mm)	Area per Bar (mm^2)	Spacing (mm)	Orientation Angle (Deg)	Position (mm)
Nylon	1	0.2	1.19	0	0.5
Polyester	1	0.2	1	90	0.5
Steel-Ply-1	1	0.22	1.16	20	0
Steel-Ply-2	1	0.22	1.16	-20	0.5

The 3D FEM was created in two steps. First, the parts were modeled, given respective material properties and meshed individually as orphan meshes. Then, these elements are tied together using a tying algorithm. In this technique, two surfaces are specified, namely, master and slave surfaces. The outer part of the rubber tire is taken to be the master surface whereas the other elements that are tied to this base rubber tire model are taken as slave surfaces. Using this tying algorithm, the nodes on the slave surfaces are constrained with respect to the displacement of the master surfaces [35]. The two surfaces can be tied irrespective of the type of element and technique used to mesh them. Table 6.2 gives the material properties of the various materials used in this model. The material properties chosen were based on previous research work [43].

Table 6.2: Material properties of the materials used in the simulation

Material	Young's Modulus (Mpa)	Poisson's Ratio	Mass Density (Kg/mm^3)	C_1 (Mpa)	C_2 (Mpa)
Nylon	4200	0.3	3.5e-5	-	-
Polyester	10000	0.3	1.93e-6	-	-
Steel	200,000	0.3	4.085e-5		
Rubber	-	-	9.3e-7	11.3	2.26

Rubber Tire (Tread Area and Sidewall):

This is the general outer rubber tire within which the other materials are tied. The tire is first sketched in 2 dimensional space to correct dimensions and then revolved 360 degrees around a central axis to generate a full tire model in 3D space. The tire tread area is not modeled with tread blocks, however, it has grooves that would grip the ground when the load is applied and when it moves on the ground.

Once the tire is modeled into a full 3D model, grooves are cut in the cross section area of the tire based on the geometric dimensions of the tied materials; namely, nylon, polyester, steel belt and steel beads, and then revolved to get a full 3D part similar to the rubber tire. The rubber tire is modeled using the tire sizing information on the tire sidewalls so that the tire can carry load approximately up to the maximum configured limit. Maintaining the proper aspect ratio also helps give the tire sidewall some stiffness when load is applied on it. Figure 6.1 shows a full 3D model of the rubber tire drawn according to the tire sizing information, 275/80R22.5.

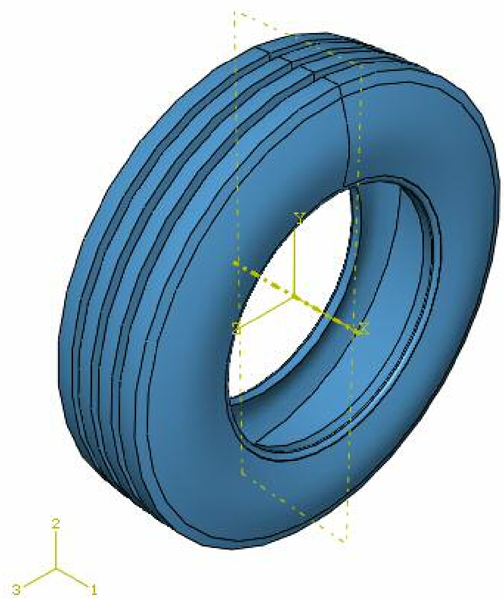

Figure 6.1: Full 3D rubber tire part

Rubber material is hyperelastic, i.e., strain lags stress and produces a hysteresis loop on periodic loading and unloading on rubber material. It exhibits both material as well as geometric nonlinearity. The area under the hysteresis curve for a cycle can be taken as the energy spent during one cycle of loading and unloading process. It is important to take into consideration the following while computing strains in rubber material [35]:

1. It is isotropic and nonlinear
2. It exhibits instantaneous elastic response up to large strains.

3. Geometric nonlinearity is accounted for in every step.

Rubber materials have very little compressibility compared to their shear flexibility and is considered to be incompressible. This behavior does not require special attention for plane stress, shell, membrane, beam, truss, or rebar elements, but the numerical solution can be quite sensitive to the degree of compressibility for 3D solid, plane strain, and axisymmetric analysis elements. In applications where the material, is not highly confined, the degree of compressibility is typically not crucial; hence, it can be considered to be fully incompressible. The volume of the material cannot change except for thermal expansion. In this simulation, the rubber material in the tire is considered to be governed by the Mooney-Rivlin constitutive equation for large strains. The Mooney-Rivlin constitutive equation for large strains is given.

$$W = C_1(I_1 - 3) + C_2(I_2 - 3) \tag{6.1}$$

where C_1 and C_2 are material constants, I_1, I2 are first and second invariants of Right-Cauchy Green strain tensor *C*. And $C = F^T F$, where *F* is the deformation gradient tensor.

The values of C_1 and C_1 can be obtained by subjecting the rubber to uniaxial and bi-axial tests. These, along with the mass density of Styrene Butadiene Rubber, are given in Table 6.2. Styrene Butadiene Rubber is the type of rubber usually used in manufacturing rubber tires.

Nylon-Ply:

The nylon-ply is modeled in a similar way as the rubber tire. It is first sketched as a 2D part and then revolved around an axis. Throughout the simulation, the global axes are maintained for modeling as well as the simulations. The x-axis is taken as the axis of revolution for all the parts. The nylon-ply is modeled as a solid homogeneous part and then material orientation is given with respect to the global axis. It is then assigned a shell section with a specific small thickness. Since nylon-ply is a reinforcement material, it is given material orientation on its surface by using rebar layers with the geometric properties described in Table 6.1. It is important to specify the orientation of these belt cords as it influences the forces at the contact patch area [14]. Figure 6.2 represents the nylon-ply which is taken as the slave part while tying it to the whole rubber tire model. A different color code is used to represent it in order to differentiate between parts.

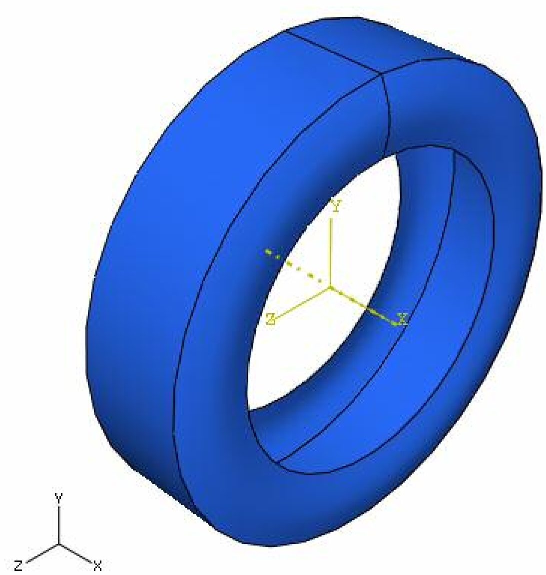

Figure 6.2: Full 3D nylon-ply

The cross sectional area of the nylon-ply is taken to be 1 mm^2 and is placed at the top of the steel-plies, just below the tire tread. The material orientation is specified to be at the top surface of the nylon-ply at a distance 0.5 mm from the central plane of the material. The orientation angle is 0 degrees, i.e., it is aligned along the circumference of the whole tire model. The rebar material orientation of nylon-ply is shown in figure 6.3.

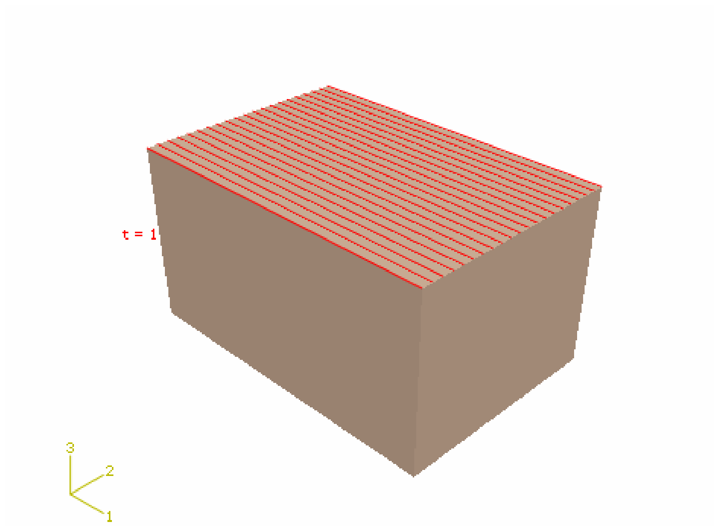

Figure 6.3: Nylon-Ply rebar

Polyester-Ply:

The nylon-ply is modeled in the same way as the nylon-ply. The x-axis is taken as the axis of revolution for all the parts. The polyester-ply is modeled as a solid homogeneous part and then material orientation is given with respect to the global axis. The polyester-ply is placed below the steel-ply to give the sidewall some stiffness to loading. It runs from bead to bead of the tire and is tied to the master rubber tire. Although the polyester-ply is modeled as a solid element, it is then assigned a shell section with a given specific thickness. This enables the assignment of rebar layers to the surface of the polyester-ply to orient the direction of the material. Fully developed 3D polyester-ply is shown in Figure 6.4.

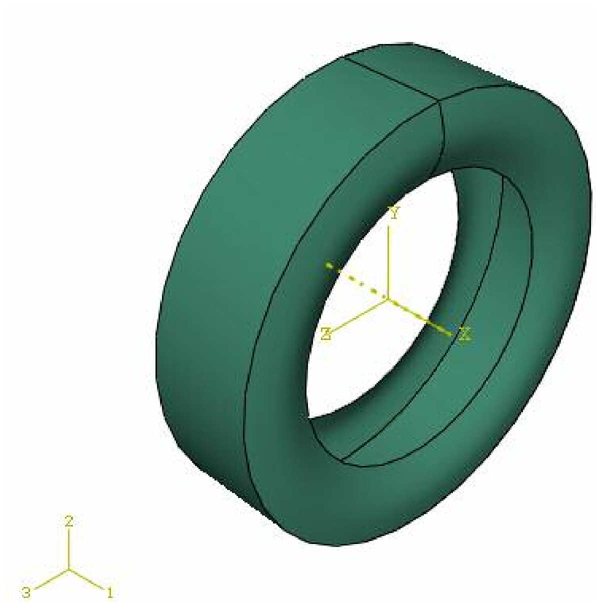

Figure 6.4: Full 3D Polyester Ply.

The cross sectional area of the polyester-ply is taken to be 1 mm^2 and is placed below the steel-plies. The material orientation is specified to be at the top surface of the nylon-ply at a distance 0.5 mm from the central plane of the material. The orientation angle is 90 degrees in order to represent a radial tire, i.e., it is aligned at an angle of 90 degrees from the circumferential axis of the whole tire model. The rebar material orientation of nylon-ply is shown in Figure 6.5.

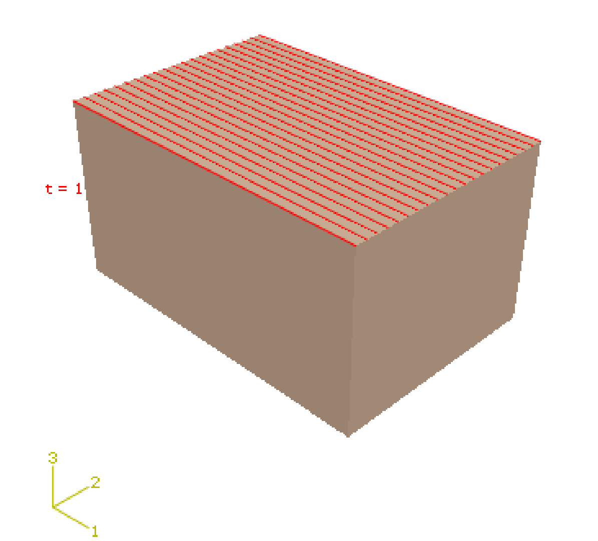

Figure 6.5: Polyester-Ply rebar

<u>Steel-Plies:</u>

Steel-plies are used in vehicle tires to give it strength to hold the axial load acting on it. These plies of steel are placed between the nylon and polyester plies below the tire tread region. These plies bear most of the weight acting on the tire at the road/tire interface. The steel-plies in this simulation is modeled as a composite ply with two layers of steel with same material properties but different orientation with respect to the axis. The axis of revolution is the x-axis which is the same as the other parts. These plies are modeled as solid homogeneous elements and then assigned a shell section to define rebar orientation. These plies do not extend from bead to bead, instead they are placed across the thickness of the tire tread. Figure 6.6 represents a 3D model of the steel-plies.

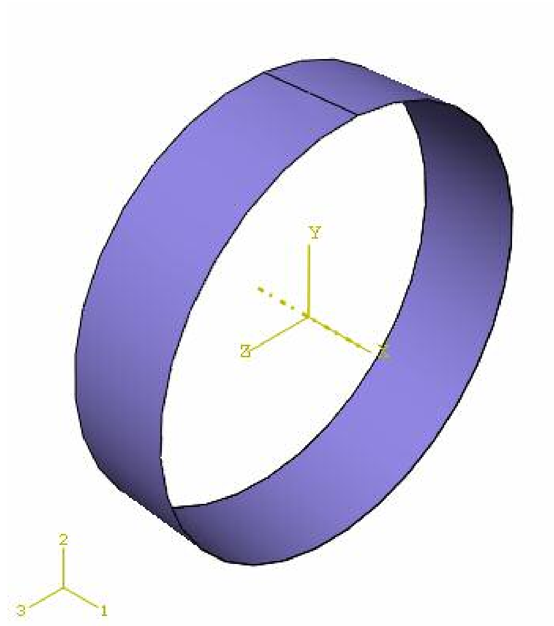

Figure 6.6: Full 3D Steel-Plies

The steel-plies are given a thickness of 1 mm^2 and the rebar orientation of +20 degrees is given at the central plane and an orientation angle of -20 degrees is given at the surface of the steel-plies. By giving such an orientation to the steel plies, it represents two steel plies placed on top of each other with each of them having their own geometric properties. Moreover, by modeling a composite lay-up, the need to model two parts separately and then tie them to the master surface is eliminated. Also, the modeling becomes simpler. The steel plies are oriented with respect to the global axis. The rebar orientation is as shown in Figure 6.7.

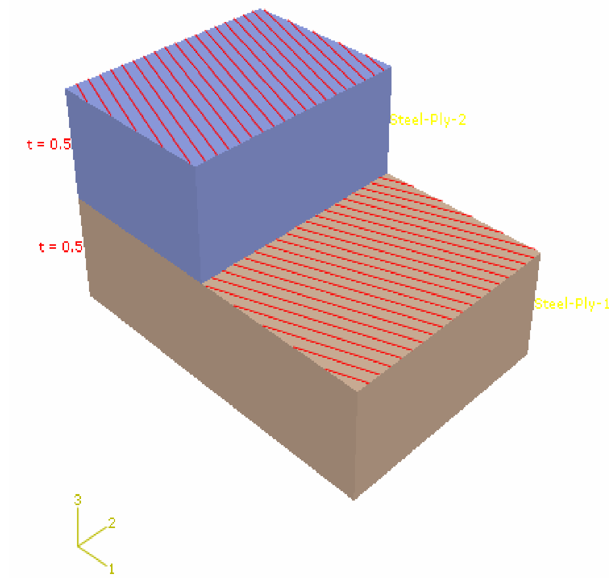

Figure 6.7: Composite lay-up of steel-plies rebar material.

Steel-Bead:

Steel beads are placed on either sides of a tire on the outer most part where the tire comes in contact with the rim. This gives the tire the required stiffness to hold onto the rim during inflation and loading. The steel beads are also used to withstand the force exerted by the road on the tire as the other parts of the tire are inflated by the inflation pressure and do not come in contact with the rim. Usually, the steel bead is nothing but a collection of a number of steel wires wound separately and tightly packed together. In this simulation, the steel bead is taken to be a single part made up of steel with geometry similar to that of the tightly packed steel wires found in tires. Taking the steel bead to be made up of a single part does not affect the tire characteristics as we are mainly interested in the contact patch area forces only. The steel bead is given a simple circular geometry and is revolved 360 degrees about the global x-axis. Figure 6.8 represents the steel beads in the tire model.

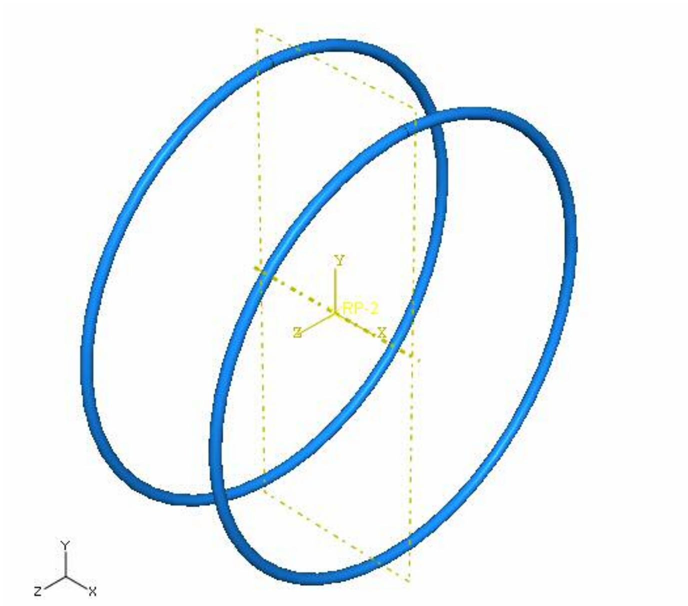

Figure 6.8: Steel Beads

Rigid Rim:

In this simulation, the wheel is not modeled as a whole part to mount the tire on it, instead two separate parts of the rim are modeled. The rims of the wheel assembly are then placed on either side of the tire where the tire would come in contact with the rim during inflation. This helps save a lot of material that would be otherwise used up if a complete wheel model was developed. As a result, the number of elements used in the simulation is greatly reduced and the computation time is lesser. The rims are modeled as discrete rigid parts, and no material properties are defined. This is done because we are not interested in the stresses developed on the rim and this, in turn, reduces the computation time as well. The rims are designed to seat the tire and also hold it, not allowing the tire to slip away while inflating the tire. Since the rims are modeled as a rigid part, reference points are created on the rim that controls the motion of each and every node on the rim. Figure 6.9 represents the 3D rigid rim.

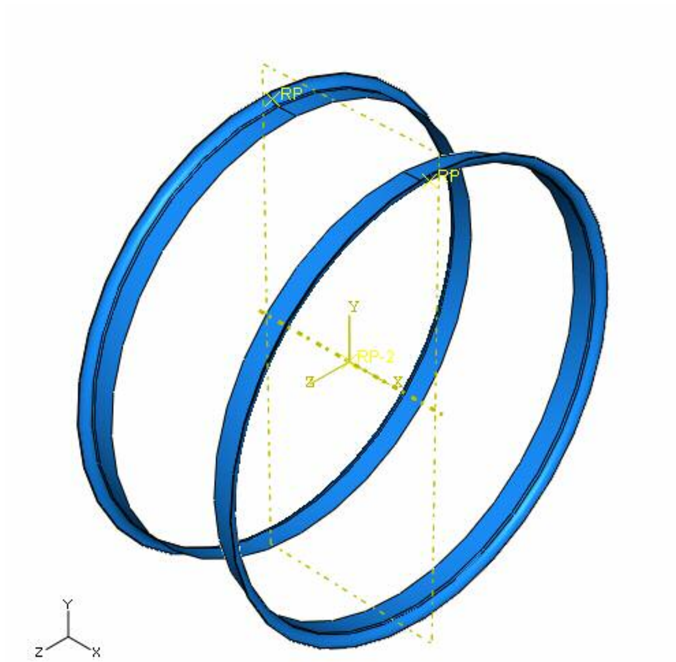

Figure 6.9: 3D rigid rim

<u>*Rigid Road:*</u>

The road is also modeled as a rigid part similar to the rims as we are not interested in the stress states in the road region. It is modeled as a discrete rigid part. Hence, a reference point on the rigid road defines the motion of every node on the entire part. Figure 6.10 represents the 3D rigid road.

All the parts were drawn to dimension and given their individual properties. Nylon, steel and polyester plies were given rebar orientation by assigning a shell section to the respective parts. An instance of all the parts was created to form an assembly and the slave nodes were tied to their respective master elements. Then, individual analysis was conducted on the assembly for a specified step, and the field output and history output values were specified to be output at the end of every analysis step.

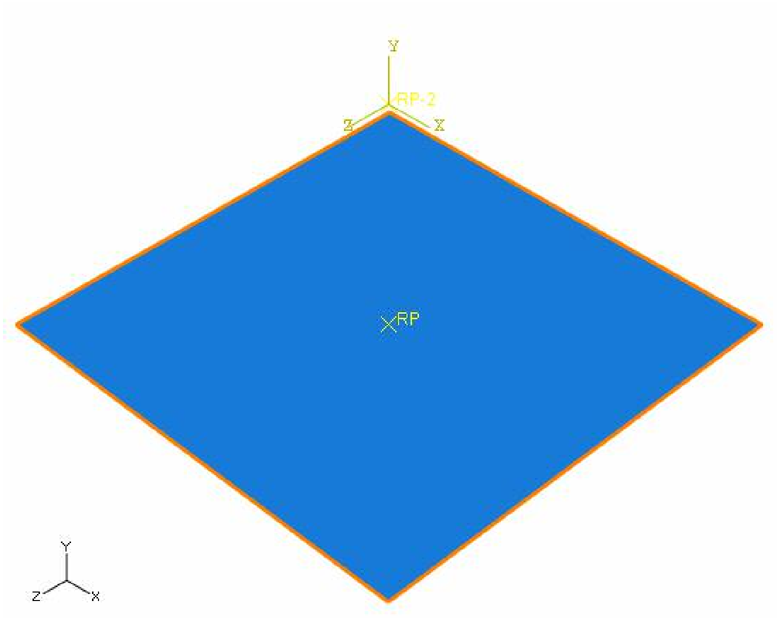

Figure 6.10: Full 3D rigid road part

Tire Analysis

Once all the parts have been correctly assembled, a mesh has to be created for every part using a specific technique that would be best suitable for that part. Since all the parts are obtained by revolving the sketch about an axis, revolved meshing technique can be used to generate mesh for all the parts. Using ABAQUS, either the assembly can be meshed on the whole or each part can be individually meshed and then joined to the assembly. In this simulation, since each part belongs to a different family of elements, an orphan mesh of each part is individually developed and then assembled back together. While the rubber tire and steel beads belong to the family of solid elements, nylon, polyester and steel plies belong to continuum shell element family. Also, rim and road elements are modeled as rigid elements and belong to rigid element family.

All the solid elements were meshed with 8 nodes, linear brick, reduced integration C3D8R elements, whereas the ply elements were meshed with 8 nodes, quadrilateral continuum shell SC8R elements. The rigid body elements were meshed using R3D4 elements, which is a 4 node 3D-bilinear rigid quadrilateral element. An orphan mesh was created on each of these parts and then assembled together to run the simulations. The simulation was conducted in two stages. First, the tire was mounted on the rims and inflated with a specific pressure on the inner walls of the tire. Then, a load was applied on the tire to run footprint analysis. During the footprint analysis, the tire was fixed to its position and the road element was made to contact with the tire by applying force on one face of the element. Although this does not simulate the real road condition, it closely simulates the axial loading condition of the tire.

During the inflation analysis step, the rims are fixed and the tire is mounted over it. A uniformly distributed pressure is applied on the inner walls of the tire, and the tire is free to move over the rim surface until it comes in contact with the rim walls. The load applied on the inner walls of the tire is applied over a time period of about 10 seconds and is applied as a smooth step, i.e., the load is applied by following a gradually increasing cubic path over time. Since ABAQUS explicit calculates the load as a function of time, a mass scaling factor of 10^{-3} is given so that explicit solves the problem at a faster rate. By giving a mass scaling factor, the mass density of the elements is scaled to determine the time step by which each incremental iteration is conducted. Since the load is applied gradually over a smooth time step and there is no sudden impact loading, the results obtained are not affected by the mass scaling factor.

<u>*Tire Inflation Analysis:*</u>

This is the first step of any tire analysis where the modeled tire is first mounted on the wheel or the rims, as it is in this case, and inflated. To model the inflation of a tire on the wheel, pressure of a given magnitude is applied on the inner surface of the tire and let to inflate on the wheel. As pressure is applied, the tire slides on the surface of the wheel until it comes in contact with the walls of the rim and holds on to it. The steel beads take up the pressure to give a robust fit on the wheel. As the inflation pressure is applied, the forces are transferred within the various layers of the tire. During this analysis, the rims are fixed so that they don't move when the tire comes in contact with it. Figure 6.11 shows a cut section view of the tire as the tire is inflated on the rigid rims.

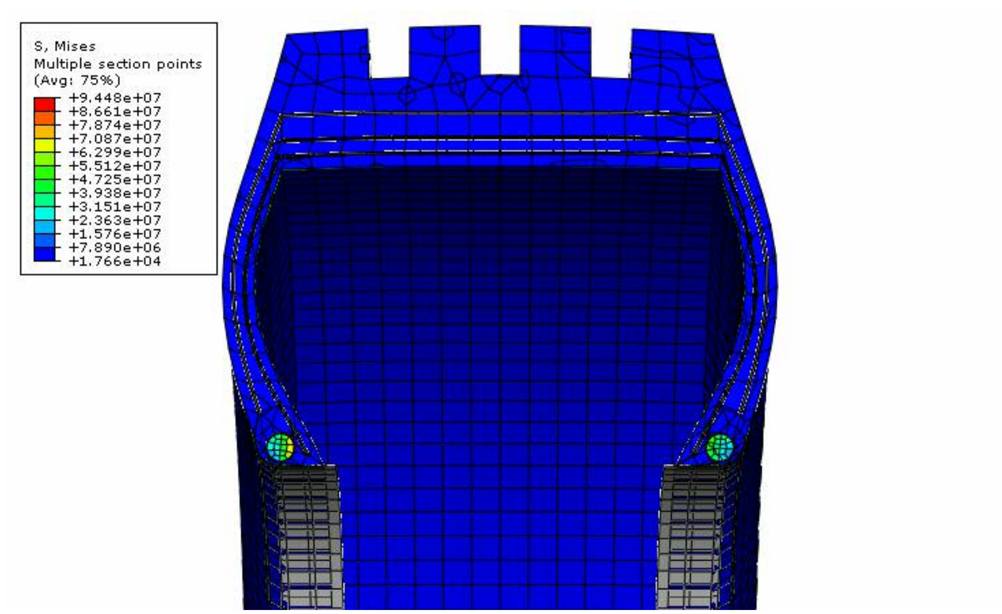

Figure 6.11: Cut section view of a tire during inflation

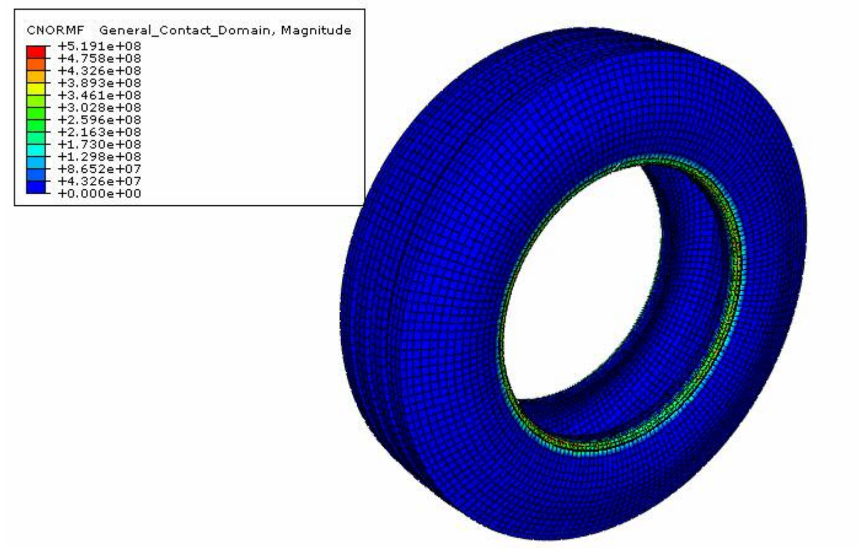

Figure 6.12: Full 3D model of a tire during inflation

From Figures 6.11 and 6.12 it can be observed that the steel beads take up the stresses that are created as a result of impact of the tire on the rim walls. These images of the tire were obtained when the tire was inflated to an inflation pressure of 517,000 kPa. It is this pressure inside the tire that gives it stiffness and strength to hold the load acting on the tire tread surface. These contact patch forces in turn jump through material boundaries and get propagated through various materials such as nylon, steel and polyester plies. The inflation step is conducted for a time of 15 seconds in ABAQUS/EXPLICT. At every time step the stresses at the contact area and other materials are recorded.

Footprint Loading Analysis:

This is an important step in analyzing the tire forces acting at the tire/road interface. The footprint analysis gives an insight on the behavior of the tire to loads acting at the axle. During footprint analysis of a tire, the contact force magnitudes and patch area can be observed to varying pressure and load cases. In this research, footprint analysis was conducted for 2 inflation and loading cases. This was done to analyze the influence on load and inflation pressure on the tire contact patch area as it is the contact patch forces that are responsible for the rolling resistance offered against tire motion.

In this analysis, the tire is first inflated to a pressure of 517,000 kPa and a load of 2500 N is applied at the tire axis acting vertically downwards. The contact force magnitude is first analyzed for this load condition and then a load of 1000 N is applied at the tire axle for the same inflation pressure. This helps us analyze the effect of axle load on the tire for a constant inflation pressure of 517,000 kPa. Such footprint analysis is useful especially for conducting tire rolling analysis on rigid road surface with give frictional coefficient.

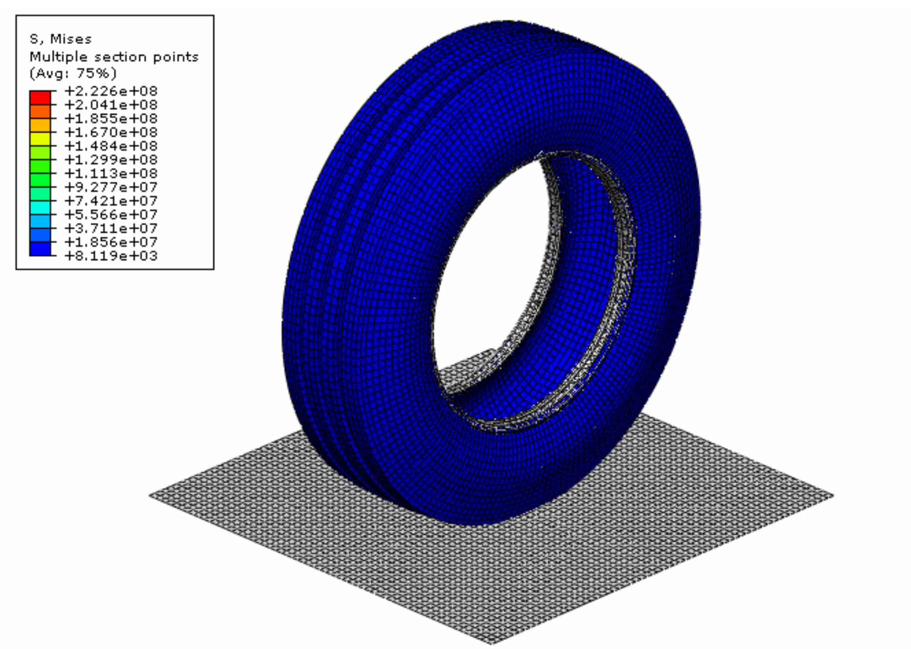

Figure 6.13: Loading the tire against rigid road surface

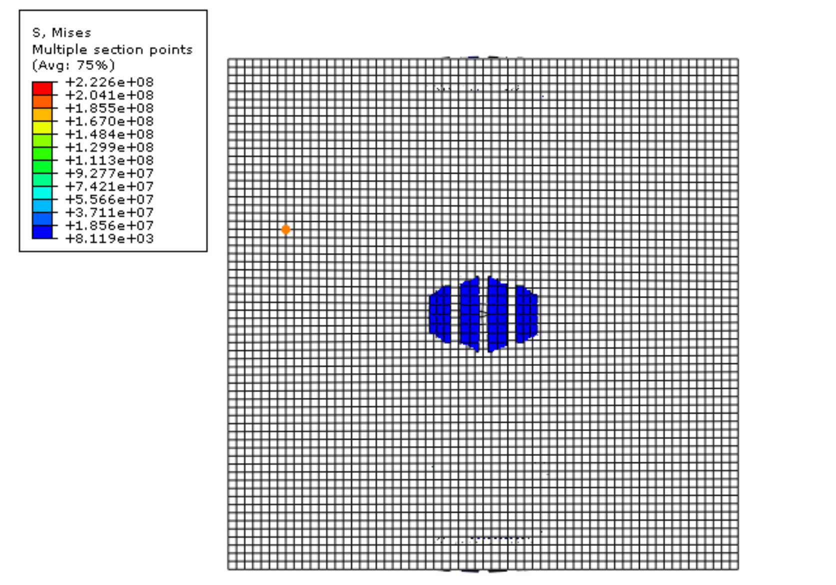

Figure 6.14: Contact patch area of a loaded tire

Figure 6.14 shows an image of the tire contact patch area created by an inflation pressure 517000 kPa and a vertical load of 2500 N. In general, by being able to determine the contact patch area of the tire, calculating the stresses and strain in the tire contact region becomes possible. Figure 6.15 shows the forces acting in the contact domain of the tire.

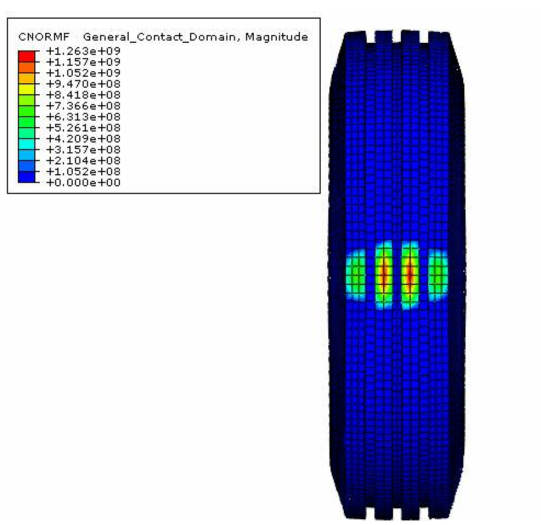

Figure 6.15: Magnitude of normal force in tire contact domain

From Figure 6.15 it can be observed that the forces are maximum at the centre and slowly reduce towards the outer parts of the tread region.

Similarly, footprint analysis was conducted on the tire inflated to same 517,000 kPa and a vertical load of 1000 N is applied. Figure 6.16 show footprint loading for a load of 1000 N.

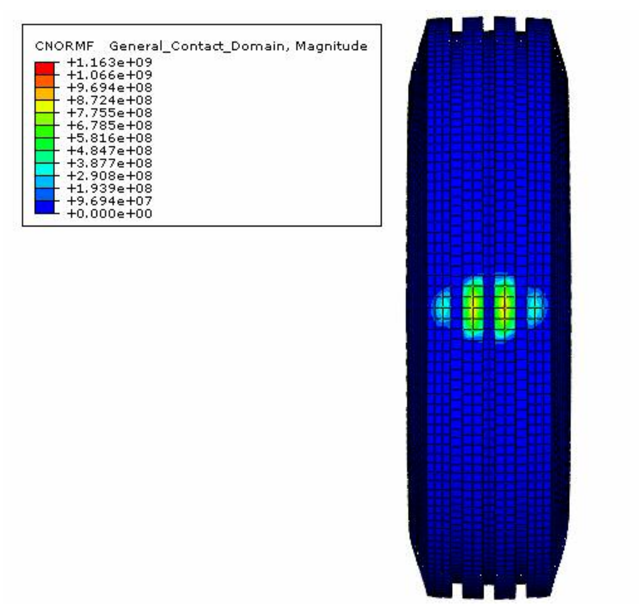

Figure 6.16: Footprint of tire with 1000 N vertical load

Figure 6.16 shows that the magnitude of the contact force is lesser for a load of 1000 N acting on the tire with same inflation pressure of 517,000 kPa. The contact patch area is also smaller compared to Figure 6.15. This clearly indicates that contact patch area increases with increasing normal load for same inflation pressures.

Figure 6.17 shows the magnitude of vertical load of 2500 N on a tire with inflation pressure of 450,000 kPa. It can be observed that even for a lower vertical load, at low inflation pressure, the magnitude of the contact force is large in the contact patch area.

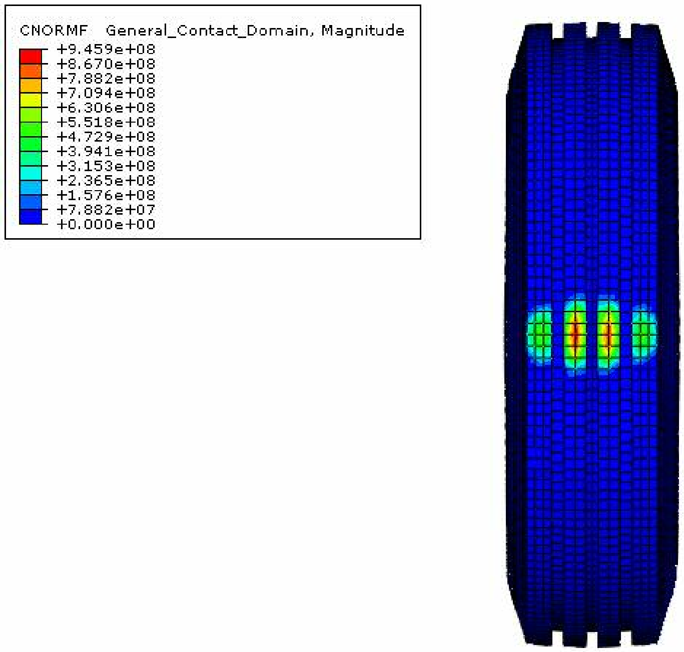

Figure 6.17: Foot print of tire with 2500 N loading

Hence, it is evident from the results that inflation pressure plays a major role more than velocity or even vertical load. In determining the contact patch area of a tire, the forces acting at the tire contact patch are responsible for the rolling resistance of rolling tire. Therefore, it is important to maintain inflation pressure to maintain optimum contact patch area so that rolling resistance is reduced.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

All the results obtained from testing the tires under various conditions, clearly prove that nitrogen filling in vehicle tires can reduce rolling resistance. As a result of reduction in rolling resistance, the tire wear is reduced, its life increases and improves the fuel efficiency of the vehicle. All the tests were conducted taking into account only the influence of inflation pressure on rolling resistance which has a significant effect on rolling force offered to vehicle motion.

The mathematical model considered for this study proved to be an effective one as it clearly shows how various parameters could affect rolling resistance. This model was flexible enough so that the influence of one parameter could be determined while all others could be kept as constant values. The experimental procedure was also motivated, by first finding if nitrogen inflation really served the purpose of this research work.

The results obtained through this effort seem to surpass some of the results obtained by previous research works. While previous research works reported that rolling resistance could only be reduced by about 30% to 50%, this research work has demonstrated that rolling resistance of truck tires could be reduced by about 70% using nitrogen inflation. Nitrogen tire filling not only had benefits of reducing the cost spent on fuel and tires, but also had a positive effect on the environment. All these benefits when put together, might help in developing a tire system that will improve the fuel efficiency of vehicle by inflating tires with nitrogen gas.

Recommendations and Future Works:

The experiments that were conducted can be extended to investigate how much each parameter, other than inflation pressure, contribute towards rolling resistance in tires. Speed tests can be done to predict the heat built up in tires due to road input and how will this affect nitrogen inflated tires. Measuring rolling resistance by varying each and every parameter could provide a complete picture which would be helpful in further improving fuel efficiency.

New experiments could also be designed that would measure the hysteresis in tires due to deformation of the rubber compound while operating on normal driving condition. Since tire is a very complex structure a number of elements that go into its construction contribute to the rolling force, it is important to run simulations to predict rolling resistance by varying geometrical as well as material parameters to measure their influence on tire deformation and temperature rise in tires.

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