

**Retread Tire Performance Evaluation Comparing to New Tire and
Applying Quality Tool to Improve the Retreading Process**



Sadik Gizaw

A Thesis Submitted to
The Department of Mechanical Engineering
School of Mechanical, Chemical and Material Engineering

Presented in Partial Fulfillment of the Requirement for the Degree of Master's
in Automotive Engineering

Office of Graduate Studies
Adama Science and Technology University

February, 2024

Adama, Ethiopia

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DECLARATION

I hereby declare that this Master Thesis entitled **“Retread Tire Performance Evaluation Comparing to New Tire and Applying Quality Tool to Improve the Retreading Process”** is my own work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

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I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled “**Retread Tire Performance Evaluation Comparing to New Tire and Applying Quality Tool to Improve the Retreading Process**” prepared under my guidance by **Sadik Gizaw** submitted in partial fulfillment of the requirements for the degree of Master of Science in Automotive Engineering. Therefore, I recommend the submission of the revised version of the thesis to the department following the applicable procedures.

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We, the undersigned, members of the Board of Examiners of the thesis by **Sadik Gizaw** have read and evaluated the thesis entitled “Retread Tire Performance Evaluation Comparing to New Tire and Applying Quality Tool to Improve the Retreading Process” and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirements of the degree of Master of Science in Automotive Engineering.

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ABSTRACT

The automobile industry has developed rapidly, leading to a significant increase in the production of scrap tires. Tire recycling has become a valuable and environmentally recognized recycling technology, and there is a growing need to promote energy conservation, emission reduction, and the development of a green recycling economy. Tire retreading is a type of recycling that extends a tire's useful life by effectively utilizing the tire's core value at the end of its useful life. However the performance and cost of the various retread tire types have come under scrutiny in recent years, as retreaded tires have been known to exhibit failure phenomena like early wear, aging, and tearing. This has a significant impact on both the safety of the user and the application of the retreaded tire. The purpose of this study is to analyze the performance of retreaded tire by comparing to new tire of the same model and to investigate the economics of retreading by comparing it to the purchase of new tires. A 3-D finite element model of retread and new tire were developed using ANSYS workbench to predict their static responses at different load and inflation pressure. Wear test was done to get comparative performance of retread tires from a company of Ethiopian Construction Works Corporation and the statistical results were used as inputs to evaluate the performance. The simulation results show that, while the retread tire's simulation result is slightly higher than the new tire's, the equivalent stress, total deformation, contact area, and ground pressure distribution of the two tires are fairly comparable. The experimental results show that retread tires mile age is 13 % lower but cost per km of travel is 37 % lower compare to new tire. Retreaded tires can have a lower failure rate and often have an equivalent lifespan to new tires if tire casings are extensively inspected and tested, and pre-cured tread or mold-cure rubber compound is selected with the intended use in mind. Finally, a proposal for further work in the subject has been made, as well as ideas for other projects.

Keywords: *retreaded tire, finite element, analysis, on vehicle road test, non- linear materials*

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TABLE OF CONTENTS

Contents Number	Page
CHAPTER ONE.....	1
INTRODUCTION	1
1.1 Background.....	1
1.2 Statement of the Problem.....	2
1.3 Objectives	3
1.3.1 General Objective	3
1.3.2 Specific Objectives.....	3
1.4 Significance of the Study	3
1.5 Scope.....	4
CHAPTER TWO.....	5
LITERATURE REVIEW.....	5
2.1. Conceptual Literature	5
2.2. Tire Remanufacturing Phase.....	8
2.3. ANSYS workbench	11
2.4. Finite element method	11
2.5. Static structure analysis	14
2.6. Mechanical Property of Tire	15
2.7. Tire Wear	24
2.8. Previous Works.....	27
2.9. Research Gap	28
CHAPTER THREE	30
MATERIALS AND METHODOLOGY.....	30
3.1 Materials	30
3.2 Methodology.....	30
CHAPTER FOUR	44

RESULT AND DISCUSSION	44
4.1 Simulation Result.....	44
4.2 Experimental Test Result.....	55
4.3 Result of Retread Tire’s Defect Analysis.....	66
CHAPTER FIVE	70
CONCLUSION AND RECOMMENDATION.....	70
5.1 Conclusion	70
5.2 Recommendation	72
5.3 Future Work	73
5.4 Limitation	74
REFERENCES	76
APPENDICES	81

LIST OF FIGURES

Figure	Page Number
Figure 2.1: Major components of a tire	7
Figure 2.2: Collected old tires for retreading.....	8
Figure 2.3: Buffing machine.....	10
Figure 2.4: Vulcanizing machine.....	11
Figure 2.5: Final Inspection of hardness and tread depth.....	11
Figure 2.6: Tire Stiffness.....	17
Figure 2.7: SAE Tire Coordinate System	18
Figure 2.8: Behavior of a Tire under Traction.....	19
Figure 2.9: Behavior of a Tire under Braking	19
Figure 2.13: Tire Camber Properties	23
Figure 3.1: 2D FE tire structure	32
Figure 3.2: FE 2d tire components.....	32
Figure 3.3: FE 2d tire meshing.....	36
Figure 3.5: FE 2d to 3d mapping	39
Figure 3.6: Load vs deflection.....	40
Figure 3.7: Testing retread tire deformation under vertical load	40
Figure 3.8: Deflection of retreaded tire under physical test vs simulation in response to vertical load.....	41
Figure 3.9: Tread depth gauge	41
Figure 4.1: Stress distribution at 2.5 bar and 3000N.....	45
Figure 4.2: stress distribution at 2.5 bar and 4000N.....	45
Figure 4.3 Stress distribution at 2.5 bar and 5000N	46
Figure 4.4: Stress distribution at 3.5 bar and 3000N.....	46

Figure 4.5: Stress distribution at 4.5 bar and 3000N.....	47
Figure 4.7: Total deformation at 2.5 bar and 3000N	49
Figure 4.8: Total deformation at 2.5 bar and 4000N	49
Figure 4.9: Total deformation at 2.5 bar and 5000N	49
Figure 4.10: Total deformation at 3.5 bar and 3000N	50
Figure 4.11: Total deformation at 4.5 bar and 3000N	50
Figure 4.13: Contact area at 2.5 bar and 3000N	51
Figure 4.14: Contact area at 2.5 bar and 4000N	52
Figure 4.15: Contact area at 2.5 bar and 5000N	52
Figure 4.16: Contact area at 3.5 bar and 3000N	52
Figure 4.17: Contact area at 4.5 bar and 3000N	53
Figure4.20: Tires removed from the study because of early damage.....	58
Figure 4.21: One of retread tires removed from the study because of excessive wears	58
Figure 4.22: One of retread tires removed from the study because of tread separation.....	60
Figure 4.23: One of new tires removed from the study because of irregular wear.....	61
Figure4.23: Tread Wear for Different Travelling Distance of New and Retreaded Tire	61
Figure 4.24: Wear rate by wheel position after 20,000 km of vehicles travel.....	62
Figure 4.25: Mileage comparison of new vs retread tire	63
Figure 4.26: Mile age prediction by project	64
Figure 4.27: Measuring Tread depth	65
Figure 4.28: Mile age prediction by wheel position	65
Figure 4.29: Cost per km of new vs retread tire.....	66

LIST OF TABLES

Table 3.1 Available Data for TRAIANGLE Tire Construction.....	32
Table 3.2: Parameters of rubber material.....	35
Table 3.3: Material of rim and bead.....	35
Table 3.4: Material parameters of old tire body and belt layer.....	36
Table 3.5: Element number and type of the uneven-spaced tire model.....	36
Table 3.6: Deflection of tire under physical test vs simulation in response to vertical load.	41
Table 4.1: Total Deformation response for pressure and load variation.....	50
Table 4.2: Contact Area of new and retread tire for pressure and load variation.....	53
Table 4.3: No. of tires removed from the study by early damage.....	56
Table 4.5: Categories of defects and their possible causes	67
Table 4.6 Suggested Actions to Reduce the Defects	68

ABBREVIATIONS

ECWC - Ethiopian Construction Works Corporation

FEA – Finite Element Analysis

ISO - International Organization for Standardization

NHTSA- National Highway Traffic Safety Administration

WT – Waste tire

CHAPTER ONE

INTRODUCTION

1.1 Background

Recycling has replaced disposal as the method of choice for a variety of waste streams, including waste rubber, as a result of growing environmental and sustainability concerns (Williams P T, 2003). The increasing global production of waste tires (WT) is a current hot study subject. A total of over 1,500,000,000 pieces of WT were made in 2011, according to (Williams P T, 2013). Up until recently, the majority of WT was illegally discarded in open spaces or landfilled. Approximately 4 billion WT are stockpiled or dumped in landfills around the world (Danon B et al., 2015). This kind of polymeric waste takes up a lot of space is bad for the environment and people's health. Discarded tires provide an ideal breeding environment for insects. One of the major issues associated with dumping WT in open areas is the increasing number of tire fires. Tire fires not only contaminate important natural objects for humans such as soil, groundwater, and air, but they also emit up to 3-4 times more mutagenic missions than oil, coal, and wood combustion in utility boilers (Pakdel H, and Pantea D M, 2001).

The environment has long been regarded to be negatively impacted by road traffic as well as the growing concentration of global wealth in the automotive sector. At the turn of the millennium, there were more than 500 million automobiles on the planet (Dabic et al., 2012), and in the years to come, this number is predicted to increase to over one billion. At the moment, landfills serve as the final resting place for 25% of all automobiles (Suterland, 2000). The current level of scientific, technical, and technological development indicates that the figure of one billion vehicles on world roads is out of date, implying that there are many more.

The vehicle is a complicated product with many parts and components made of different materials. One of these parts that significantly affect the economy and the environment both during and after vehicle use is the tire. One of the industrial products that produce the most solid waste is tires. Tires, which are composed of 30–40 kg of rubber and steel wire material and are used for two–three years before being discarded, are included in every passenger car that leaves the assembly line.

The typical lifespan of an automobile with three sets of tires is 11–12 years. As a result, each car adds 10 kg of used tires to the waste stream each year if they are not recycled in some way. On a larger scale, the quantity of tires discarded annually in a nation like France is equal to 250,000 tons. Thankfully, used tires are sometimes useful. When a used tire is replaced, many of its essential qualities, including shape, rigidity, impermeability, and lateral strength, are still present. Tire retreaders have looked into a few of these characteristics.

In many cases, the only physical property lost by the tire during its first life is surface adhesion. While the lack of adhesion makes the tire unsuitable for its original application, remanufacturing or retreading is still an option. Furthermore, if a specific tire does not meet the technical and economic conditions for retreading, the cycle can be closed using one of the numerous rubber reclaim methods (Pieter J.H. and others, 2001).

1.2 Statement of the Problem

Although the tire industry has grown quickly alongside the automobile industry, tires are one of the industrial products that generate the most solid waste. Therefore, each car dumps 10 kg of used tires into the waste stream annually if they are not reused in some way (Williams P T, 2013).

Tire retreading is a type of remanufacturing that extends a tire's useful life by roughly another lifetime by effectively utilizing the tire's core value at the end of its useful life. Only 10 to 20 percent of a tire is consumed during its first lifetime, according to sources in the industry. The tread accounts for almost all of the material consumption, but it can be changed through retreading.

One of Ethiopia's largest construction firms, Ethiopian Construction Works Corporation (ECWC) is heavily involved in the building and upkeep of roads, bridges, dams, irrigation systems, hydropower generation, water supply systems, sewerage systems, and drainage. In addition to these activities, it also engages in the assembly of construction machinery and equipment, the manufacture of spare parts, the provision of maintenance services for construction machinery and equipment, the production of construction materials, and the rental of buildings, warehouses, and machinery in the construction industry.

Currently, the company owns more than 3000 fleets, which use more than 10,000 tires annually. The corporation established a tire retreading shop where the retreading process

is being done in order to lower the cost of new tires. The shop oversees the retread program for the equipment administration division of ECWC. Over the past few years, concerns have been raised about the effectiveness and cost of retreading as retreaded tires frequently exhibit failure phenomena like early wear, aging, and tearing. Research is required to compare the performance of popular brands of new tires and recaps in order to identify performance issues and the cost effectiveness of the retreading process.

1.3 Objectives

1.3.1 General Objective

The general objective of this thesis work is to provide important theoretical guidance to improve performance of retread tire and to generate data on the cost effectiveness of using retreads versus new tires.

1.3.2 Specific Objectives

The specific objectives are as follows

- To study the value-adding operations in the tire retreading process
- To study the mechanical characteristics and the failure mechanism about retread tire
- To evaluate retread tire durability via wear test
- To generate data on the cost effectiveness of using retread tire versus new one

1.4 Significance of the Study

If study is made in this area, it will definitely benefit the corporation regarding performance improvement of retreading tires, increase the experience of using retreaded tires, reduce cost of purchasing new tires and over all reduces environmental problem associated with waste tires. In addition to the financial advantages, the corporation will be able to allay concerns by proving that every type of retread available has been examined and found to function as expected in a secure and efficient manner.

1.5 Scope

In order to evaluate retreading tire performance and cost effectiveness, the analysis was performed based on the following distinct scope:

- Tire retreading performance evaluation in the scope of static analysis of tires because it has a major contribution in the tire performance and fuel economy of the vehicle.
- Tire retreading performance and economic analysis focused on only pickup trucks, it did not include tires of heavy trucks and construction machineries.

1.6 Limitation

One of the objectives of this study was to conduct mathematical model which will help to evaluate how many times retreading can be performed on a single tire and estimation retread tire mileage. But because of lack of data from the company and time constraint, I could not complete as initially intended, so I recommend future study to work on it.

A comprehensive Finite Element Model was created and employed for static examination. Transient dynamic analysis, however, is also crucial to producing a thorough evaluation result. This case needs to be taken into account in the next research in order to produce a more thorough outcome.

In addition, because of the limitations in laboratory facilities, experiments of foot print, cornering test and camber behavior could not be carried out. Laboratory tests enable different tests to be carried out for easier evaluation of the influence of different conditions.

The road surface for this tire-road combination has less of an impact on the final tire-road characteristics than do the operating conditions during the wear tests. Therefore, in order to compare the impact of road surface on the tire-road characteristics, it is imperative that all measurements be conducted under the same operating conditions. Specifically, it is anticipated that the maximum lateral force that a tire can produce will vary depending on the type of road and environmental conditions, as well as the tire's surface temperature.

1.7 Organization of the Thesis

Chapter 1 presented the motivation of doing this study and emphasized the significance of finite element method application in the process of establishing tire model for performance evaluation.

In Chapter 2, a review of the literature on tires, relevant to this study, is presented. The tire mechanical properties including tire deformation, force and friction are introduced firstly. A comprehensive review of the existing literatures related to retread tire is carried out to give a deep insight.

Chapter 3 presents the materials and methods employed in this study in which the complex material properties of rubber and reinforcement cords are investigated. A feasible and efficient wear testing procedure is summarized.

Chapter 4 summarizes the main findings of this thesis and provides a final statement.

Chapter 5 provides recommendations and the possible works for improving the thesis in future studies are provided.

CHAPTER TWO

LITERATURE REVIEW

2.1. Conceptual Literature

Before delving into the various methods of scrap truck tire treatment, it is useful to understand the tire's composition and structure. Tires are a highly complex engineering product. The inner liner, carcass, bead, sidewall, belts, under tread, and tread are the seven major components of a tire. Tires, which have been developed over several decades, can withstand stresses while also traveling a long distance before requiring retreading or replacement. Tire composition varies significantly depending on application (Hita I. et al., 2016). Tires are made up of various types of carbon black, rubber, steel cords and fabric for reinforcement, fillers such as clay, silica, and minerals or chemicals to allow or accelerate vulcanization (Williams P T, 2013), (Rowhani A., 2016).

The number of reinforcement layers varies according to tire type. Truck tires typically require more steel. The proportion of each compound varies depending on the tire application, such as motorcycle, car, and truck tires (Hita I. et al., 2016), as well as the manufacturing company. It is also worth noting that each company has its own method of making tires, which is considered intellectual property and is usually not open to the public, but the ingredients that are primarily used in tire manufacturing are the same.

The process of completely replacing a tire's tread and, occasionally, the sidewall rubber on a worn tire with high structural integrity is known as retreading. Following that, a curing process is applied to the repaired tire, which forms the tread pattern and vulcanizes the new rubber to the casing. Over the years, tire manufacturers have invested a lot of money in product research to create tires that are meant to last not just a single life but also a second and even a third.

The retread industry has grown steadily as a result of stronger casings, better remanufacturing methods, a wider range of specialized rubber compounds, and the desire to recycle and lessen environmental effect. A retread tire is initially a worn tire, possibly with 2-3 mm of tread remaining and possibly having been regrooved in the past, or it may be a punctured tire in need of repair.

Following maintenance, truck tires are typically gathered and recycled as part of a routine tire

retreading process, delaying disposal and helping the environment. It is possible to restore hot or cold tread on a tire casing after fresh tread has been applied. The properties and construction method of the tread, along with the type, age, and use of the tire's casing, all influence how well a retread tire performs. The variety of casings, treads, and processing settings available for retreaded tire manufacturing significantly affects the contribution of each component.

One method for trying to extend the life of tires is retreading them. It is clear that the goal of retreading is to produce profitable outcomes because new tires are much more expensive than retreads. There is an ecological component as well: retreading tires lessens the amount of natural resource exploitation and its negative environmental effects. Furthermore, fewer wastes are released into the environment while still ensuring the requisite level of exploitation safety. Owing to these reasons, this treatment is often used on the tires of a wide range of transportation vehicles, including trucks and buses used for internal transit, airplanes, and group vehicles used for road transportation.

Consideration should be given to the tread wear and degradation of a tire when determining whether to discard or retread it.

In their paper, (Beukering and Janssen, 2001) assume that retread tires travel the same distances as new ones. The assumption made by (Ferrer, 1997) is that the quantity of retreads has no bearing on a tire's service life.

Tire components

The components of the tire listed below can be also be seen graphically in figure 2.1(Williams P T, 2013).

- **Inner liner:** A synthetic rubber layer that serves as an air tight layer is the first interior material. This is done to stop any air leaks that might cause the tire's pressure to drop.
- **Carcass:** Rubber housing surrounds a structure made of durable textile fiber cords. Its goal is to keep the tire's form when under internal pressure. This makes sure that when the tire is inflated, it won't bulge out.
- **Beads:** The steel wires that make up the beads are a part of the tire sidewall that touches the rim. The wires' function is to ensure an airtight connection so that there is no air leakage between the tire and the rim, which would cause the tire pressure

to decrease. The wires used are robust. Some tires have wires built into them that can support ten times the weight of a car.

- **Sidewalls:** The sidewall is where the tire's production information and the manufacturer's logo are printed. Preferably, the information includes the tire's dimensions, speed rating, preferred rolling direction, and the month and year that it was manufactured.
- **Steel belts:** Rubber is reinforced by steel belts bound into it. As a result, the tire is better able to withstand the pressure from turning and is kept from expanding due to the centrifugal force produced by rapid rotation.
- **Cap plies:** The cap plies, which are situated between the steel belts and the treading, are rubber layers with integrated nylon that wrap around the circumference of the tire. This layer both increases resistance to expansion and lessens friction-related heating.
- **Tread:** The part of the tire that makes contact with the ground and is visible is the tread. The quality and characteristics of the tire's performance are largely determined by this component. The tread's goal is to offer traction against the road's surface while producing little heat or abrasion. Based on their calculations and testing, each manufacturer uses their own material composition and tread pattern that they believe to be the best choice for a given set of circumstances.
- **Grooves:** The cuts in the tread that create the tread patterns are called grooves. The purpose of the treading is to reduce road noise, divert water, and provide a large contact area with the proper frictional coefficient.

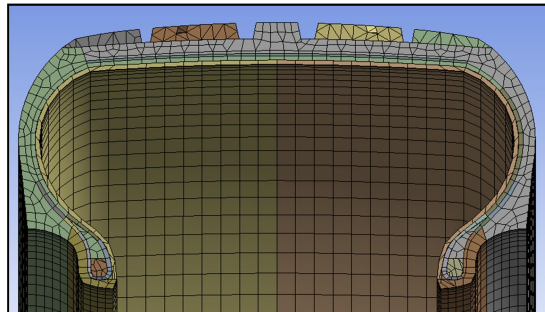


Figure 2.1: Major components of a tire

2.2. Tire Remanufacturing Phase

Tire remanufacturing is an industrial process that calls for industrial equipment, skilled labor, and high-end development methods. Due to the needs and goals for the finished products, each retreading plant may operate differently.

According to the NHTSA, the entire tire retreading procedure is as follows:

Step 1: Casing Submission

Used casings (cores) arrive at the retreading plant. Each casing has a distinctive identification code stamped on it that allows it to be distinguished from other casings according to its type, circumstances, and necessary processing.



Figure 2.2: Collected old tires for retreading

Step 2: First Stage Inspection

To check for physical flaws on the tires (such as bumps, holes, cuts, punctures, nails, etc.), a skilled technician visually inspects the tire by glancing at various parts of the tire. The technician also uses judgment to determine whether the tire meets plant, industry, and quality standards for safety. The retreading stream rejects tires that do not adhere to the expected inspection protocols, such as those with significant side damage.

Step 3: Second Stage Inspection

The testing of the casings that advance to this stage is more thorough and in-depth in order to detect damages and flaws that are not visible to the naked eye. There is testing equipment available for identifying internal casing flaws. In addition, additional non-destructive testing, like shearography, is performed to find internal casing flaws with a laser. Its goal is to guarantee that the shoulder, sidewall, and bead are in good condition.

Step 4: Buffing

The remaining tread of the casings that have passed testing is removed during the buffing process. By doing this, the old, worn tread design is removed, and the casing is ready for the new tread. To buff the tire to the desired tire radius, profile, and crown width, the buffing process is streamlined.



Figure 2.3: Buffing machine

Step 5: Casing Preparation and Repair

The shaved casing is checked once more after the buffing process is finished to ensure that there are no visible defects and that the casing has not been harmed in any way. At this point, any casing that does not adhere to the necessary testing standards is rejected.

Step6: New Tread Application

The fresh tread is positioned and set up for chemical bonding with the casing. The new tread is centered and properly aligned with the casing.

Step 7: Enveloping

The applied tread and the casing are wrapped around a rubber envelope and a vacuum is generated.

Step 8: Curing (Vulcanizing)

The rubber envelope's casing and tread are placed in a curing chamber where they are exposed to a set temperature and pressure, which causes the curing process to take place. By enabling the cross-linking of rubber polymeric chains between the tread and the casing, the curing process aims to chemically bond the tread to the casing. Two common methods are used to apply the new tread to the tire before retreading are: (1) mold-cure process; (2) pre- cure process.

Uncured tread is applied to the casing and strip wound during the mold-curing process. In order to cure the tread rubber and mold the tread design onto the unvulcanized rubber, the casing and tread are then put together in a rigid mold and heated to almost 300 degrees Fahrenheit.

Pre-curing involves applying and strip-winding tread rubber that has already been cured and incorporates the tread design to a casing that has been shaved. The remaining tread is joined once the casing's circumference has been completely contained. Between the tread and the casing, a thin layer of uncured rubber is placed, and it is then cured to provide chemical bonding b/n them.



Figure 2.4: Vulcanizing machine

Step 9: Final Inspection

The cured tires are delivered to a platform for final inspection, where the retreaded tires are put through standard industry testing. Retreaded tires are specifically tested to eliminate any with anomalies or separation between the tread and casing.



Figure 2.5: Final Inspection of hardness and tread depth

2.3. ANSYS workbench

For the simulations in this thesis, ANSYS Workbench version 22R1 was employed. Powerful software like ANSYS Workbench can help with solving challenging engineering problems. This program can simulate different metaphysics problems like heat diffusion, stress and strain analysis, fluid mechanics, and more, and it produces accurate and trustworthy results. Numerous large corporations with diverse areas of expertise use the well-known software ANSYS. Ferrari, for example, used it for aerodynamic studies to save several hours of costly wind tunnel testing while designing their hyper car, the Ferrari LA Ferrari. This demonstrates how accurate and valued software programs such as ANSYS Workbench are in the industry today (E. Cardile, 2013).

2.4. Finite element method

Numerical analysis, in particular Finite Element Analysis (FEA), has become more prevalent over the past 20 years in all stages of tire design. Because it divides the entire structure into finite elements and determines the structure's mechanical properties by integrating the

corresponding variables on the element's nodes, the finite element method may be more accurate and applicable for tire realistic simulation. The FEA is currently replacing some tire tests.

Various finite element models were developed at the University of Birmingham to simulate tire behavior. Andrew Burke (Narby, E., 2006) investigated tire/road interaction and tire dynamic response characteristics using the finite element code MSC/NASTRAN and a shell element model.

Different inflation pressures and hub loads were used in the simulation of tire/road interaction modeled by the gap element formulation, producing accurate results when compared to experiments. Burke's work (Narby, E., 2006) also used a cleat test to shed light on the enveloping properties in the time domain as well as the response of a rolling tire to inputs from the road. Only hub loads and inflation pressures at 0 slip and 0 camber angle were taken into account, though. Using the finite element program ABAQUS, (E.O. Bolarinwa, 2004) reported on tire characteristics research at the University of Birmingham. The 2D cross-section tire profile was rotated in 3D solid elements to create the finite element tire model. The simulation of tire steady-state behavior during cornering was investigated and compared to experiments performed on the AEC tri-axial tire test rig. The relaxation length effect is specifically investigated for tire transient behavior under the influence of preload.

On the other hand, Bolarinwa's tire model was hampered by a lack of precise data regarding the geometry of the tire composite and the properties of the viscoelastic material. The number of papers on tire dynamics analysis using FEA has multiplied since the advent of commercial finite element software. (Kazuyuki Kabe and Masataka Koishi, 2000) investigated the typical tire cornering property using ABAQUS implicit and explicit. While ABAQUS/Explicit was used to describe the transient response, which included cornering force and self-aligning moment effects due to various parameter effects, ABAQUS/Standard was used to investigate the relationship between driving force and angular velocity of a steady-state rolling tire. In a number of publications, (M. H. R. Ghoreishy, 2002) examined various aspects of tire simulations. In a parametric study for steady-state rolling tires in, M. H. R. Ghoreishy took into account the type of cords, belt angle, and friction coefficient between the tire and the road. M. H. R. Ghoreishy joined the two meshed sections to create the tire with tread pattern model for the static analysis of tires with tread patterns. He examined tire cornering using

finite elements while taking the impact of belt angle into account. It is determined that a belt angle of 20 degrees might offer the best performance for the designated tire by examining the distribution of frictional shear stress and contact pressure at various slip angles and belt angles. This study demonstrated that the interlayer shear stress at belt edge zones and total strain energy can be used to predict belt separation and large tire deformation.

In a similar vein, (Ghosh, P., et al., 2007) created a finite element tire model to account for changes in tire construction, such as variable belt angle, tread material, apex height, and ply turn-up height. Using a continuum 3 dimensional, 8 node, hybrid formulation element, he produced a 3D tire model. The design matrix was taken into consideration as iterative nonlinear FEA was conducted for both the individual and interactive effects of individual parameters. The simulation results closely match the experimental data in terms of inflation and load deflection, as well as lateral, tangential, and cornering stiffness.

The intricate impact of tire parameters, such as the interaction between slip angle and camber angle, was disregarded, as well as the specifics of the tread's geometry. Combining an optimization algorithm with a finite element tire model is one of the potential and practical methods for tire design. The two main areas for design optimization are typically the geometry of the tire cross-section and the construction of the tire reinforcement. (Abe et al., 2004) investigated the topological tire structure to optimize the Young's modulus of each tire material to enhance tire performance, particularly rolling resistance.

Finite element analysis was used by (Gabriel Anghelache and Raluca Moisesescu, 2008) to examine the impact of rubber's elastic material properties on tire modal properties. The C10 coefficient of the tire tread rubber's hyper elastic material property model was adjusted incrementally within the range of values reported in the literature, and its impact on tire natural frequency was noted. The high order tire resonant frequency was found to be significantly influenced by the C10 coefficient. The finite element tire model unquestionably has many benefits and is advantageous to tire manufacturers, customers, and even tire designers. An integrated system that can seamlessly integrate the tire CAD design system and tire FEA system is needed in order to increase the efficiency of product development during the design, testing, and manufacturing processes (Bolarinwa, E.O, 2005). This integrated system is expected to have a seamless interface with vehicle dynamics simulation software such as SIMPACK and CarSim. Even for developing an integrated approach for efficient tire

FEA, there is still a long way to go.

2.5. Static structure analysis

In order to predict vertical stiffness, or the shape of the load-deflection curve, or to analyze the footprint shape and stress distribution, a static FEA can be used in tire mechanics to analyze the first function of the tire and load support (Stojkovi, M. and Trajanovi, M., 2001). By monitoring stresses and strains in cord or rubber components, it can also be used to evaluate tire durability early on. Additionally, (Cho and Jeong, 2002) noted that it is frequently used to forecast tire maneuverability using lateral stiffness or stress distribution in the tire carcass. In conclusion, by anticipating the effects of changes in tire parameters, static FEA helps to accelerate the tire design process and enhance the quality of both new and existing tires.

According to (Tönük, 2001), mounting and inflation results from static analysis of axisymmetric tire models typically include findings on bead wire stresses, the impact of tire geometry and rim size on cord stresses and contact pressure distribution at the tire-rim interface, initial tire shape after each of the two stages, and other results. Such models are correct if the loads are also axisymmetric, as the tire geometry is. With axisymmetric models, 3D models, and any non-symmetric tire loading, the same conclusions can be drawn. In applications involving vertical loads, it is important to consider the load-deflection curves, stresses in tire components, footprint shape, and contact stress distribution, among other things. Due to the overall shape and loading symmetry, only a quarter of a tire can be accurately modeled. However, this introduces some error because belt angles are not symmetric with regard to two vertical planes, one of which contains the tire axis and the other is normal to it. However, in the case of static loading, this error is usually small. For the purpose of describing the material behavior of structural tire components made entirely of rubber, various authors have used linear or hyper elastic material models. Tire deformations in service rarely exceed 40% (Tönük, 2001), and material model stability has made the Mooney- Rivlin form the most popular choice. It's still a work in progress to describe the structural elements of the tire's composite cord-rubber material. Highly nonlinear characteristics, couplings, and stresses at the cord-rubber interface are a few of the important issues that need to be looked into. By describing the macro mechanical characteristics of cord-rubber composites as equivalent to an isotropic medium, some researchers have focused on the micromechanical approach (Pidaparti, 2001). The orthotropic material definition in

combination with solid or shell, large-strain capable finite elements, as described in (Tönük, 2001) gained popularity less than ten years ago, was nevertheless frequently used by the authors who used the equivalent media approach for simplicity. The most important are numerical efficiency and the reduction of discretization-dependent errors as well as the ability to define material laws and failure criteria separately (Tönük, 2001). It is also easier to define non-linear models for cord and rubber using this method. The inner tire structure is modeled in varying degrees of detail, with some structural components that do not have a significant impact on the overall mechanical behavior of the tire being omitted or modeled in conjunction with another component. For the sake of simplicity, it is common practice to only model circumferential grooves in 3D tire models, as done by (Tönük, 2001). Such streamlined models do not significantly alter the footprints and load-deflection curves when static loads are applied. However, the distribution of contact stress differs significantly and there is a small difference in vertical tire stiffness. (Danielson et al., 2006) further assert that the results of the analysis are unaffected significantly by removing the half of the tire model above the horizontal plane containing the tire axis. However, only the portion of a detailed tread shape that will make contact with the ground is taken into account when modeling it. The sidewall carcass contour was optimized using an axisymmetric tire model while (Tönük, 2001) experimented with simplified tread shapes and built a fine mesh in the contact zone with transitions to the rest of the model.

2.6. Mechanical Property of Tire

The structure and behavior of a vehicle tire are so complex that it would be impossible to discuss all of their mechanical characteristics in this section. The pertinent and predominate tire mechanical properties are reviewed here in order to give context for the subsequent simulation of retreaded tires.

2.6.1 Tire Deformation

While in use, tires are subjected to a variety of loads, including inflation pressure, mechanical loads that are applied from the outside, and thermal loads (Hall, W., 2003). These loads, along with contact with the wheel rim and road, cause the tire's geometric shape to change. Deformation is the technical term for this. This deformation can be represented by the displacement of specific tire locations.

The relationship between mechanical load and tire displacement that characterizes the tire flexibility, or stiffness, is made up of the effects of inflation pressure and the rigidity of the tire's structure. Deformation results in internal and external stresses and strains in the tire. The behavior, performance, and durability of tires can be described using their reactions to loads (Hall, W., 2003).

2.6.1.1 Tire Vertical Stiffness

According to (Ramji, 2001), tire vertical stiffness affects the characteristics of vertical vibration and ride behavior of the vehicle. It is calculated as the ratio of tire vertical force to vertical deflection.

In (Ramji, K., 2001), various methods for determining tire vertical stiffness are described. By gradually applying a chosen value of vertical force and measuring the deflection, or vice versa, one can determine the static stiffness of a stationary tire. Sweeping a frequency range with small amplitude sinusoidal excitation on the tire axle can be used to measure the dynamic stiffness of both non-rolling and rolling tires. Vertical tire static and dynamic stiffness is influenced by a variety of factors, including tire type, preload, inflation pressure, rim width, and others.

2.6.1.2 Tire Longitudinal Stiffness

The ratio of tire longitudinal force to tire longitudinal deflection is commonly used to define tire longitudinal stiffness. Investigation of longitudinal cushioning of road irregularities that cause tire shimmy is crucial. Only non-rolling tires can have their longitudinal stiffness measured by applying a longitudinal displacement or a rotational angle to the rim. Before the tire completely slides, the displacement or angle value is quite small. The longitudinal stiffness in the rotation case is the longitudinal force brought on by the angle of rim rotation. According to (Ramji, K., 2001), the longitudinal stiffness obtained by the aforementioned two methods may differ.

2.6.1.3 Tire Lateral Stiffness

The ratio of tire lateral force to tire lateral deflection is known as the tire's lateral stiffness. In order to measure the lateral stiffness of a stationary tire, a lateral displacement is applied to the rim. This measurement can be used to examine the relaxation characteristics of a rolling tire. Divide the tire lateral stiffness by the cornering stiffness to get the lateral relaxation length. The oscillation of the tire in the lateral and yaw directions depends on the lateral tire

stiffness. Generally, a tire is most stiff in the longitudinal direction and least stiff laterally (Ellis, j. R.,1996), Namely $K_x > K_z > K_y$ as shown in Figure 2.6.

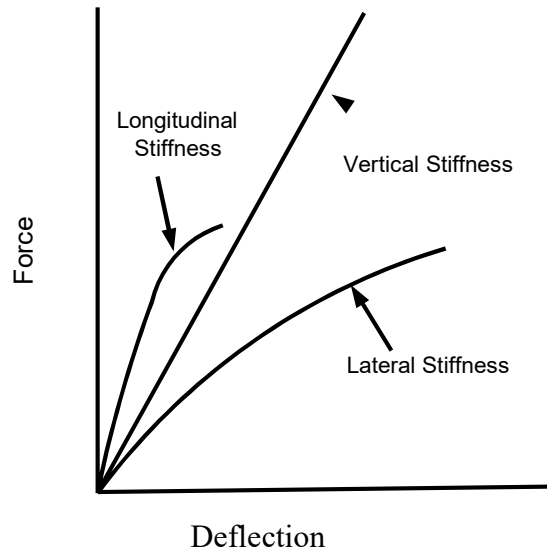


Figure 2.6: Tire Stiffness

2.6.2 Strain and Stress

The strain and stress states of a tire in use can give crucial information about the tire's operational behavior due to the complexity of tire structure and material properties, especially when subjected to extreme operating conditions.

Understanding how stress and strain are distributed and how much they are exerted in key tire areas like the breaker edges and carcass turn-up edges can help us predict when a tire design will fail. S. L. Sokolov created a finite element tire model using bulk isotropic elements to analyze tire stress concentrations and forecast failure regions (Sokolov S.L., 2007). According to (Wang et al. 2002), early tire failures due to fatigue may be caused by the buildup of stress and strain, particularly in the crucial transition zones between the tread and casing. They investigated the stress and strain along the bond line between new tread and casing for a retreaded tire using experiment and finite element analysis. In addition to the tire strain and stress research that is related to fatigue, the strain and stress state can also be seen as a different reflection of tire global behavior. The strain and stress state of the tire is specifically connected to the operational circumstances of the tire. However, it is very challenging to model and validate strain and stress, especially internal strain and stress, in order to get accurate results.

2.6.3 Tire Force and Moment

The coordinate system provided by the Society of Automotive Engineers (SAE) is depicted in Figure 2.7, and it is used in this study to introduce the tire force and moment characteristics. The longitudinal, lateral, and vertical directions of the tire are represented by the axes x , y , and z , respectively. The z axis is parallel to the ground, and they are perpendicular to one another. Tire longitudinal force, lateral force, and vertical force are the translational forces F_x , F_y , and F_z along the three axes, respectively. The tire overturning moment, rolling resistance moment, and aligning moment, respectively, are the rotational forces (moments) M_x , M_y , and M_z about the three axes.

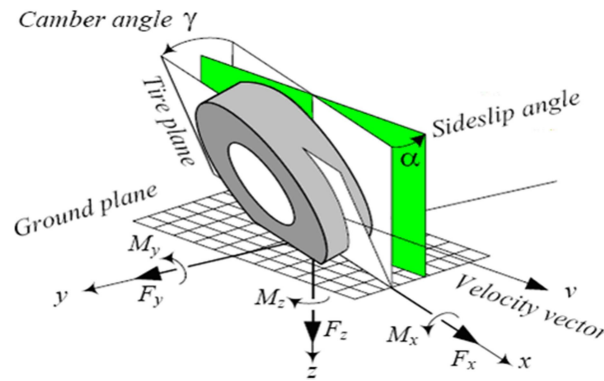


Figure 2.7 SAE Tire Coordinate System

The contact patch's normal and shear stresses, which are distributed, result in the tire force. Tire moments are produced by the uneven distribution of normal and shear stresses. The friction coupling effect between the tire tread and the road causes the shear stress to be the cause of the generation of longitudinal and lateral forces. Surface adhesion and hysteresis are the two main mechanisms that contribute to the friction coupling effect.

The tire forces and moments not only react to the driver's input at the tire/road contact patch, but also give the driver the ability to change the vehicle's direction and maintain the expected lane of travel. The characteristics of vertical vibration and ride quality of a vehicle can be improved by controlling tire vertical force. The optimization of tire longitudinal force control can enhance vehicle braking/traction performance and lower fuel consumption, while the control of tire lateral force typically benefits the vehicle's stability and cornering. Tire force and moment modeling has been covered in a lot of literature.

2.6.4 Traction and Braking

The longitudinal deflection of the tire and the friction between the tire and the road both affect a tire's traction and braking capabilities. The longitudinal shear stress causes the compressed tread element that was in the contact patch before the rolling tire gained traction to bend forward. Due to the longitudinal shear stress in the opposite direction, the tread element on a rolling tire experiences stretching and back bending before making contact with the road. Figures 2.8 and 2.9, respectively, can be used to depict the traction and braking states of a tire (Wong J.Y., 2001).

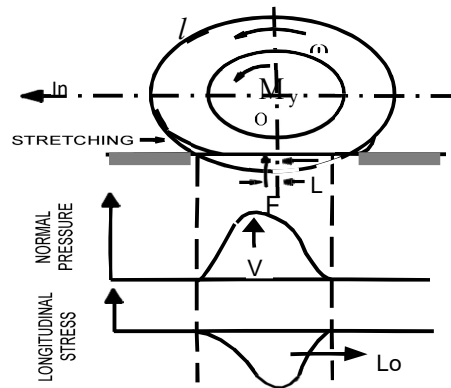


Figure 2.8 Behavior of a Tire under Traction

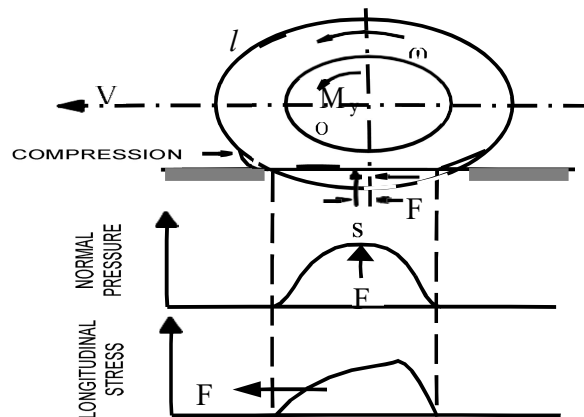


Figure 2.9 Behavior of a Tire under Braking

In the contact patch, where the tire tread deflects to create and maintain the friction force, or braking force, braking occurs when the tire is moving at a linear speed greater than its circumferential speed about the y axis. Similar to this, traction force is produced when the tire rotates around the y-axis at a slower rate than its circumferential speed. Simply put, the

difference between tire rolling speed and travel speed is what generates the traction and braking forces.

The tire is in steady state rolling when the longitudinal slip is equal to zero, that is, when the product of the tire rolling speed and the effective radius equals the tire travel speed. The tire is under braking when the longitudinal slip is negative. The tire is under traction when longitudinal slip is positive, i.e., tire rolling speed multiplied by effective radius is greater than tire travelling speed. According to Figures 2.10 and 2.11, which depict longitudinal slip, the braking and traction force can be expressed as a function (Milliken, W.F., 2006).

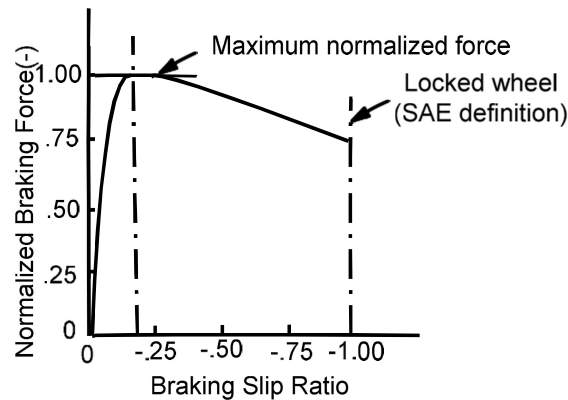


Figure 2.10 Typical Braking Slip Ratio Curve; Slip Angle= 0°

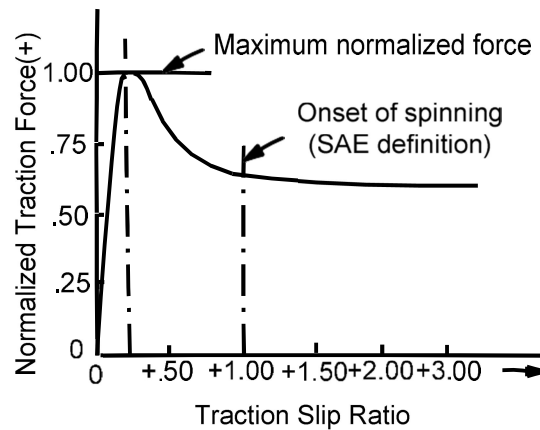


Figure 2.11 Typical Traction Slip Ratio Curve; Slip Angle= 0°

It can be found that the longitudinal force increases with the longitudinal slip until the slip ratio reaches around 0.2. Then it reduces rapidly and the wheel will be locked or onset of spinning when the longitudinal slip ratio is equal to -1.0 or 1.0.

As aforementioned in (Milliken, W.F., 2006), the tire traction and braking properties are dependent on a variety of factors such as vertical load, tire inflation pressure and surface

friction, etc.

Cornering Characteristics

A lateral force will be produced at the tire/road contact patch when a vehicle receives steering input to perform a lane change operation. This tire's ability to turn is primarily affected by how the slip angle and camber angle change as the tire turns.

Slip angle

When lateral slip occurs, both the tire sidewall and the tire contact patch are deformed. In this instance, Figure 2.12's illustration of the generation process of lateral force by slip angle uses the deformation of the tire contact patch (Gillespie, T.D., 1996).

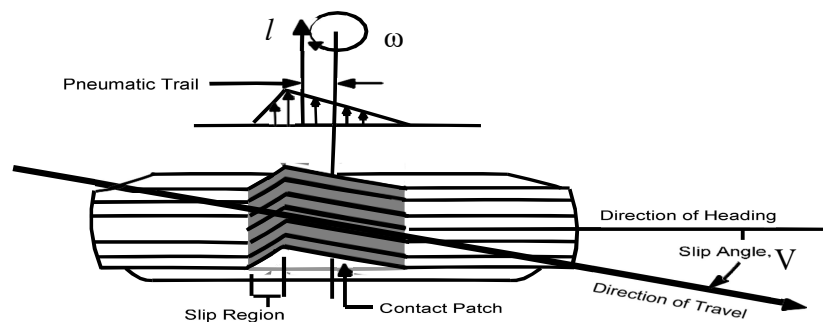


Figure 2.12 Rolling Tire Deformation under Cornering

The rolling tires' tread element experiences two states as a result of the lateral force: lateral deflection and lateral slide. The tread element's lateral deflection first increase as it enters the contact patch, increasing the lateral shear stress. The state balance force is maintained during this process, and the tread element is kept in the location of their initial contact with the road because the resultant of lateral shear stress is still less than the lateral friction force. However, the tread element will slip to the side if the lateral shear stress resultant is greater than the available friction. It is discovered that the rear portion of the tire contact patch is where the difference between lateral deflection and lateral slide occurs. Due to the asymmetry of the force build-up process, the lateral force that results is sometimes located away from the center of the contact patch. Both a lateral force and an aligning moment can be converted to the center of the contact patch. The pneumatic trail is the separation between the actual position of the lateral force and the center of the contact patch.

The negative slope at zero slip angle is referred to as the cornering stiffness. Lateral slip is the tangent of the slip angle. During cornering, there is a transfer process between the current steady-state tire and the previous steady-state tire. To generate the lateral force necessary to

reach the steady-state force condition, the tire must complete between 50 percent and one revolution.

Camber angle

Another element that may contribute to tire cornering force is camber angle. A rolling tire with a camber angle will cause the tread and tire carcass to deform, producing a camber thrust (lateral force). The elliptical path that the rolling tire will take is caused by camber thrust. As seen in Figure 2.13, the camber thrust is always pointed in the direction that the tire is inclined.

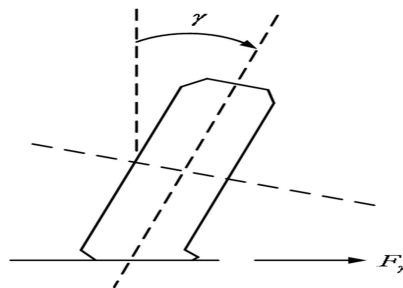


Figure 2.13 Tire Camber Properties

Camber stiffness is defined as the ratio of camber thrust to camber angle. The range of the camber angle is typically less than the maximum range of the slip angle. It is well known that the slip angle contributes more to tire cornering force than the camber angle does.

Additionally, a number of factors, including tire size and type, number of plies, cord angles, wheel width, tread pattern, etc., affect how well a tire corners. One of the motivations for the development of intelligent tire technology is the use of real-time information about tire cornering force for vehicle stability control.

2.6.5 Tire/road Friction

One of the key aspects taken into account when braking, cornering, and tire traction is tire/road friction. The estimation of tire/road friction becomes important for the development of tire active safety system as well as vehicle dynamics control system.

Only the friction coupling between the tire and the road can increase the traction/braking force and the lateral force beyond that point. As previously mentioned, friction is produced by the rubber hysteresis mechanism and surface adhesion. It is discovered that surface adhesion, not the hysteresis mechanism, is what primarily contributes to the friction force. However, the effect of surface adhesion is primarily influenced by the state of the road, with dry roads

providing more friction than wet ones.

For a variety of slip angles and slip ratios, the friction circle provides the diagram of lateral force vs. longitudinal force (Milliken, W.F., 2006). The friction circle encircles the entire region of curves. Any point on the curve denotes a combined traction/braking and cornering situation. The tire working condition should consistently remain close to the friction circle limit in order to maximize the vehicle's performance. The development of tire/road friction estimation technology is a result of the profound understanding of the friction condition, such as the potential friction and used friction, which is very important for achieving reasonable and efficient driving operations.

2.6.6 Equivalent stress in ANSYS workbench

In ANSYS Workbench, the equivalent stress tool is a useful tool that enables the display of three dimensional stresses as a single positive stress value, which is frequently shown on the model as color contouring. Formula (1) is used to calculate the equivalent stress, or von Mises stress as it is also known.

$$\sigma_e = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}} \quad (1)$$

The sigmas in the formula are called principal stresses. These are derived from the plasticity theory, saying that “an infinitesimal volume of material at an arbitrary point on or inside the solid body can be rotated such that only normal stresses remain and all shear stresses are zero”. Where σ_1 is maximum stress, σ_2 is middle stress, and σ_3 is minimum stress. To be used in formula (1) these principle stresses are always ordered like $\sigma_1 > \sigma_2 > \sigma_3$. The equivalent stress can be expanded to include in the maximum equivalent stress failure theory. This is often related to as von Mises yield stress criterion and can be used to predict the yield point, or maximum yield stress, for a ductile material. A ductile material is a material that deforms under tensile load unable to return to its initial shape, also called plastic deformation.

2.7. Tire Wear

According to Rosen Ivanov (2016), wear is the definition of material removal from a surface as a result of frictional interaction with another surface. Tire wear is characterized as a complex phenomenon because it is frequently measured or estimated after a considerable amount of time has passed, during which time the wear process may have been influenced by

a number of processes other than sliding friction. These procedures may involve mechanical, physical, or chemical elements, among others. Adhesive and abrasive wear are two commonly recognized mechanical wear mechanisms that influence tire wear.

Adhesive Wear

Adhesive wear is one of the most fundamental types of wear since it happens when two solid surfaces come into contact (Rosen Ivanov, 2016). The adhesive process causes some of the softer material to migrate toward the harder surface (Rosen Ivanov, 2016).

A sliding motion that creates bonds at the contact location in conjunction with a high local pressure there can explain this. As a result of the bonds being broken to the side of the softer material by constant sliding, material moves from the softer surface to the harder one.

The most significant influences on the total amount of material being transmitted are the characteristics of the surfaces and the surrounding environment (Rosen Ivanov, 2016). In terms of environmental conditions, adhesive wear increases with temperature.

Because the bonds formed are atomic in size and a higher temperature affects the rate of chemical reaction, adhesive wear happens more quickly (Rosen Ivanov, 2016).

Frictional heat is frequently generated when two surfaces rub against one another, raising the temperature.

Abrasive Wear

(Rosen Ivanov, 2016) defines abrasive wear as the surface loss of solid material. The substance is gone because a harder surface is gouging it out. There are two main scenarios in which abrasive wear can happen: first, when a harder surface rubs against a softer surface; second, when a third body—typically a grit particle—gets stuck between two surfaces and is harder than the other two. The third body in the second scenario can choose to abrade both surfaces simultaneously or just one of them.

Fatigue

When two surfaces come into contact during rolling, the wear and tear from the repeated stresses under rotation may cause indentations in the surfaces (Rosen Ivanov, 2016). When two surfaces are under load, the maximum shear stress, or force per unit area, occurs at a small, finite distance below the surface, and the distribution of elastic stresses in each surface's material is close to the contact area (Rosen Ivanov, 2016). When fatigue cracks first appear, they usually begin to develop in the vicinity of the point of maximum stress.

Aging Effects

A variety of chemical processes cause tires to lose some of their beneficial properties after five years of use on a vehicle or room temperature storage (A. N. Gent and J. D. Walter, 2006). One of the processes involves a chemical reaction between ozone and the unsaturated elastomers used in the compounds (A. N. Gent and J. D. Walter, 2006). Ozone cannot penetrate the material directly, so the reaction occurs at exposed surfaces and can cause acute fissures to form. More material is exposed by the cracks as they form, allowing ozone to react with it and creating more cracks. Oxidation, a reaction with atmospheric oxygen, is another process that causes aging effect (A. N. Gent and J. D. Walter, 2006). In comparison to the ozone reaction, this process is usually slower, but oxidation usually occurs at a deeper level. Instead of producing cracks directly, oxidation makes the material more brittle and hard. The material's increased hardness is a result of the formation of new crosslinks, the reaction of hydrocarbon elastomers with oxygen, and the interaction of the material with nearby molecules. As the cracks grow, more material is exposed, which invites ozone to react with and produce even more cracks. Another process that ages people is oxidation, which is a reaction with atmospheric oxygen (A. N. Gent and J. D. Walter, 2006). This process is typically slower than the ozone reaction, but oxidation usually takes place at a deeper level. Oxidation causes the material to become harder and more brittle rather than directly causing cracks. The creation of new crosslinks, the reaction of hydrocarbon elastomers with oxygen, and the material's interaction with surrounding molecules all contribute to the material's increased hardness (A. N. Gent and J. D. Walter, 2006).

The development of new crosslinks, the reaction of hydrocarbon elastomers with oxygen, and interactions with nearby molecules are what cause the material's increased hardness, according to (A. N. Gent and J. D. Walter, 2006).

Conditions Affecting Tire Wear

There are numerous different conditions that influence the overall tire wear, ranging from different characteristics in road surfaces to the driving style itself.

Surface Influence

Tire wear is directly influenced by the coarseness and sharpness of the road surface (A. N. Gent and J. D. Walter, 2006). The season can also affect how a road's surface is constructed. In moderate climates, winter conditions usually result in a smoother road surface than summer

conditions.

Construction Influence

A stiffer tire construction generally produces a less amount of tire wear, where the stiffer construction includes effects of tread pattern and stiffness in the tread compound (A. N. Gent and J. D. Walter, 2006).

Driving Influence

The driving style, characterized by the velocity and accelerations, has shown to have a significant impact on tread wear and the tire's lifetime (A. N. Gent and J. D. Walter, 2006). With an increasing vehicle velocity, the lifetime of the tire is greatly reduced.

2.8. Previous Works

The tire is a relatively soft or flexible, pneumatically pre-stressed structure whose behavior depends on applied loads and operating conditions. All those behaviors happen in the contact patch (called footprint) between the tire and the pavement. In the tire-pavement contact issue, footprint shape and pressure distribution are the foremost factors for tire wear and mileage performance, and have significant influence on vehicle control ability and braking behavior. It is obviously that there are correlations between the tire footprint and other properties of the tire including traction, braking, interaction noise, wear, etc (ENT A N and WALTER J D, 2005). Generally, the discussion of tire footprint mechanics or physics involves footprint geometry, tread pattern geometry, stresses, characters of contact pressure distribution (M. Pottinger, 2005).

Researches on footprint can provide reference for modifying tire design. That is why the footprint shape analysis is also performed during quality control of tire production. By virtue of the importance of the tire-ground contact issue, a lot of experiments have been performed. Applying to various techniques, equipment and methodologies, engineers and researchers have published an extensive literature and obtained some useful results. (IVANOV, et al, 2008), investigated the contact patch area of various automobile tires using visual processing in response to normal loading on the wheel and tire inflation pressure. These studies are useful to obtain the 3D tire-ground footprint area by visual processing, but accuracy pressure distribution in the contact area between tire and road cannot be acquired for instruments limited.

G. Ferrer (1997) investigated the value-adding steps involved in tire retreading. The research determined that the decrease in the time between retreads caused by material fatigue was the best way to choose the number of times a tire should be retreaded to maximize its utilization. Whether a tire has been retread or not, its cost varies depending on how long it has been since the last one. In order to quantitatively describe the mechanical characteristics and the failure mechanism of retreated radial tires, (Qi Xiao-jie and Wang Qiang, 2008) studied the ground mechanical characteristics of load vehicles' retreated tires. They discovered that as the load of the retread tire increases, the pressure on the tire shoulder increases while changing slowly relative to the central ground region. Additionally, as the load of the retread tire increases, the ground area increases.

(Baptiste Lebreton and Axel Tuma, 2006) conducted research to determine the profitability of remanufacturing tires for cars and trucks and to determine how far remanufacturing operations could be expanded. A real-world case study analysis of the current state of the truck and auto tire markets allowed for a thorough investigation of the profitability of remanufacturing operations. And they discovered that remanufacturing lowers a new tire's manufacturing costs while also enhancing the tire industry's sustainability.

A test system was established to forecast the residual life of the retreaded tire and matrix on the finite element simulation and performance tests of the loading bearing capacity for the retreaded tire in another study on the prediction technology of the retreaded tire residual life by (Qi Xiao-jie and Wang Qiang, 2008). The study established theoretical guidelines for estimating tire matrix life and using safety performance. The method combines performance testing technology with computer simulation conveniently and affordably. It also adopts system hardware that requires little up-front investment and contributes significantly to quick testing and low operating costs. (Anurag Sharma, 2013) studied on the overall cost of retreaded tires per km and found out that the cost of a tire is decreased by using retread tires without altering their outer diameter or their strength.

2.9. Research Gap

Some key findings from the literature review and other areas are listed below. For the production of high-quality remanufactured tires, retreading is a well-established and regulated process. Retreaded tires must pass a strict quality inspection that complies with new tire regulations. Retreads are incredibly popular and are typically used on non-steering rear axle

locations. How many times retreading can be done on same tire depend up on tire usage. Retreaded tire can worn out very early it depend up on its processed effect. Tire retreading reduces per km tire cost of vehicle.

However, there aren't many studies that compare the mechanical characteristics of new and retread tires to assess how well they perform. Furthermore, resonance phenomenon needs to be taken into account because retreaded tires are commonly used on uneven roads in the construction industry which cause significant vibrations. This study is unique in that it combined the simulation results with the on-vehicle wear test to improve the evaluation of retread tire performance and its cost effectiveness.

CHAPTER THREE

MATERIALS AND METHODOLOGY

3.1 Materials

3.1.1 ANSYS Workbench

The finite element model constructed by ANSYS Work-bench 22 R1 software was used. The simulations in ANSYS Workbench were performed with their feature Static Structural Simulation, which uses finite element method when solving problems.

ANSYS uses the material properties, support conditions and loading conditions to solve equations for each node in all its degrees of freedom.

3.1.2 Tread depth gauge

Tread depth gauge is a simple tool to measure tire tread depth in increment of 1/32 “or mm. A millimeter and calibrated tread depth gauge shown in figure 3.1 was used to measure the tread depth of tires in this study.

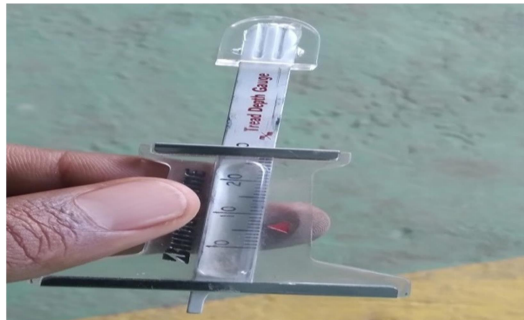


Figure 3.1: Tread depth gauge

3.1.3 Pareto chart

The Pareto chart is an excellent quality tool for identifying significant issues in the system. It is made up of a sequence of bars, the heights of which represent the frequency or severity of issues. The bars are organized in ascending order of height from left to right. This indicates that the issues depicted by the tall bars on the left are more crucial than those represented by the short bars on the right (Karuppusami, G., and Gandhinathan, R, 2006). The tool is incredibly helpful in identifying the issues that have the most significant cumulative effect on the system. Furthermore, the tool renders ability to categorize the issues according to the

weight of impact so that the necessary actions can be employed in a prioritized manner. The literature states that approximately 80% of the issues arise from 20% of the causes in any system. The appropriate data must be gathered and analyzed from the process or system which is under scrutiny in order to produce a Pareto Chart (Jayswal et al. 2011). When the list of issues contains a mix of problems including both the issues with potentially major repercussions and issues with minor consequences, one of the following two approaches can be used, (i) the author weighting method to adjust count frequency, or (ii) frequency analysis paired with a cost or exposure Pareto chart. The various versions of the basic Pareto chart are routinely used in quality improvement approaches to identify the bulk of issues that may arise due to small reasons (Benjamin, S. J et al. 2015).

3.2 Methodology

3.2.1 Finite Element Analysis (FEA)

Finite Element Analysis is a numerical simulation method widely used in engineering to predict the behavior of complex structures under various loading conditions. In this study, FEA was employed to model and analyze the equivalent stress, the total deformation, contact area and contact stress distribution of both retreaded and new tires. The FEA software utilized allows for accurate representation of the tire's structural properties, material behavior, and boundary conditions.

The construction process that was used to simulate a retreaded tire in a virtual environment is described below. The tire chosen for virtual replication is a TRIANGLE 7.50R15LT. This chapter covers the used programs, construction method, challenges, constraints, available data, and overall development to the full model.

3.2.1.1 Structure of FE Retreaded Tire Models

The overall geometry of the physical tire that was requested to be modeled in a FEA environment was required prior to the modeling process starting. Before the majority of this research was conducted, it was decided to try to replicate A TRIANGLE 7.50R15LT. Some of the geometry was easy enough to learn from published materials and online brochures. However, at the time, no other geometry was available, so a real tire that had been assigned for retreading but was rejected due to side wall damage was chosen and cut into sections for

analysis. This made it easier to measure the sidewall thicknesses, under tread, and under tread membranes, which allowed for their incorporation into the FEA model. The material properties for each component of the tire model needed to be implemented after the dimensions were known. Since the manufacturer had made the material properties unavailable, the development of the retreaded tire model would incorporate the material properties found in previous similar studies.

3.2.1.2 Available Data for Construction

As was mentioned earlier in this chapter, it was possible to model this tire using its geometry, general construction layout, and similar material properties. The complete set of information has been compiled and is displayed in Table 3-1.

Table 3-1 Available Data for Triangle Tire Construction

DIMENSION	VALUE
Tire Size	7.50R15LT
Rim Diameter	381 mm
Section Width	215 mm
Unloaded Overall Diameter	780 mm
Rated Inflation	560KPa
Rated Vertical Load	1205 kg
Tread depth	9.5 mm

3.2.1.3 Construction of FEA Retreaded Tire Model

The section-cut of the sample tire was used to extract the majority of the geometry. Similar retreaded tire tread was used in conjunction with the straightforward measurements to create the tread pattern seen in Figure 3.2. The footprint was used to collect the precise geometry of the tread pattern in order to accurately replicate it.

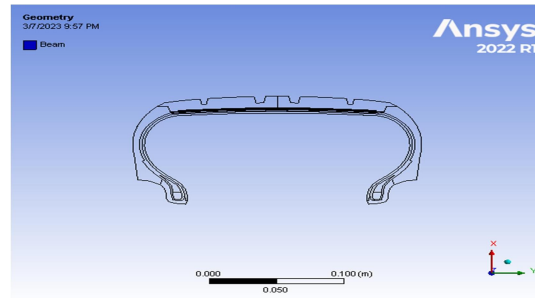


Figure: 3.2: 2D FE tire structure

To identify the tire geometry and the position of the inner layer for this work, a TRIANGLE 7.50R15LT tire was cut into small pieces. The corresponding FE tire model has eleven components, as seen in Fig. 3.2. The tire body and sidewall, which are modeled with solid elements, act as a host for the inner layers. Solid elements were used to model the tread patterns that provide traction and braking power. Shell elements embedded inside the tire body were used to model Belts 1 and 2 in the ring geometry.

In ANSYS rebar elements are used to define layers of uniformly spaced reinforcing bars in shell, membrane and solid elements. The fiber cords modeled as rebar elements were embedded in the shells (carcass and belt). The bead, which prevents the tire from popping out from the rim, was modeled with solid elements embedded inside the tire. The rim is relatively stiff, to improve the computation efficiency, it was modeled with rigid elements.

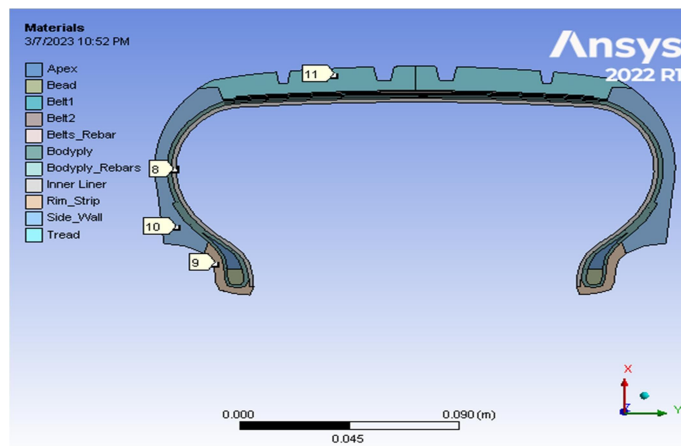


Figure 3.3: FE 2d tire components

3.2.1.4 Materials of FE tire models

Steel, synthetic fabric with high tensile strength, and rubber are just a few of the

materials used to make tires. Steel and light alloys are the primary components of rims. For the rubber's hyper elastic property, (Wang, 2003) and (Bolarrinwa E.O, 2004) applied the Neo-Hookean model to tire modeling. Mooney- Rivlin model was chosen by (Ghoreishy M., 2006) for the rubber parts of a steel-belted radial tire.

Rubber is treated as a hyper elastic material because of its high bulk modulus, which makes it volumetrically incompressible. Ansys 22R1 contains constitutive models for rubber-like materials. The strain energy potential, which specifies the strain energy stored in the material per unit of volume in the initial configuration, is used to describe the hyper elastic behavior (Ghoreishy M, 2006). The tire rubber's stress-strain behavior is predicted using the Mooney-Rivlin form. The Mooney- Rivlin strain energy potential W is:

$$\bar{I}_1 = J^{-2/3} I_1 \dots\dots\dots (3)$$

$$J = \lambda_1 \lambda_2 \lambda_3 \dots\dots\dots (4)$$

$$C_{10} = \mu_0 / 2 \dots\dots\dots (5)$$

$$D_1 = 2 / K_0 \dots\dots\dots (6)$$

Where

C_{10} material constant

D_1 material constant

$\bar{I}_1$ the first invariant of the deviatoric part of the left Cauchy-Green deformation tensor

I_1 the first invariant of the left Cauchy-Green deformation tensor

J volume ratio λ_i principal stretches

K_0 bulk modulus μ_0 shear modulus

The material parameters of the sidewall and the tread are displayed in Table 3.2.

Table 3.2: Parameters of rubber material

Component		Material Constant C10 Pa	Material Constant C01 Pa	Incompressibility Parameter D1 Pa ⁻¹	Density
Body ply	Mooney-Rivlin 2 Parameter	2.65E+05	1.40E+05	3.35E-08	1100kg m ⁻³
Sidewall		23720	2.98E+05	8.04E-08	
Rim Strip		2.64E+06	50054	1.48E-09	
Apex		2.64E+06	50054	1.48E-09	
Belt1		1.01E+06	75320	9.71E-09	
Belt2		1.01E+06	75320	9.71E-09	
Inner Liner		1.45E+05	1.43E+05	4.86E-08	
Tread		4.07E+05	34680	1.45E-08	

Composites of cord and rubber, which are used to make the carcass and the layers of the belt, exhibit anisotropy and nonlinearity in mechanics. The accuracy of the simulation results is dependent on the modeling of the cord-rubber composites. For the purpose of extending tire life, (Murat B., 2003) added steel cord reinforcements to truck tires' carcass and all-terrain tire belt areas. For the 3D analysis of car tires, he used elements that were cord-reinforced.

In ANSYS, the rebar elements and laminated shells make up the cord-rubber composites. The belt and carcass layers are referred to as rubber laminated shells, and the reinforcing cords are referred to as steel rebar elements.

The rigid rim, rigid road, and elastic bead all have these features. Table 3.3 provides the definition of a material.

Table 3.3: Material of rim and bead

Component		Young's Modulus Pa	Poisson's Ratio	Bulk Modulus Pa	Shear Modulus Pa
Rigid Rim	Isotropic Elasticity	2.00E+11	0.3	1.67E+11	7.69E+10
Rigid Road		2.00E+11	0.3	1.67E+11	7.69E+10
Bead		2.00E+11	0.3	1.67E+11	7.69E+10

Table 3.4: Material parameters of old tire body and belt layer (Wang, 2003)

Material	Elasticity modulus (MPa)			Shear modulus (MPa)			Poisson's ratio			Density/ kg/m ³
	E1	E2	E3	G12	G23	G31	μ_{12}	μ_{23}	μ_{31}	
Old tire body	9.7e4	6.96	6.96	6.04	3.26	3.26	0.398	0.398	0.48	4580
Belt layer	1.58e5	2.62	2.62	9.88	2.58	2.58	0.344	0.344	0.48	6480

3.2.1.5 Preprocessor and analysis procedure

The algorithm first transforms the user-defined simulation and design parameters into a command that contains the list of commands the preprocessor should run. For example, load curves for tire inflation pressure, vertical load, and speed; tire-road friction and contact parameters; and tire design data such as tire cross-section, mesh size, geometric, material, and damping properties. Additionally included are solution settings like hour glass control options, elements formulations, and integration step-size. The ANSYS 22R1 preprocessor then executes the command and generates the input for the solver. Depending on the type of elements chosen for the model, the user may need to re-order the default node numbering for generating the model for the ANSYS 22R1 solver.

3.2.1.6 Simulation with 2D axisymmetric tire geometry

Typically, a 2D axisymmetric tire geometry has following three parts:

- 1) Geometry of a tire cross-section.
- 2) Rigid surfaces representing the road and the rim bodies
- 3) Line bodies representing the rebar locations

It was assigned the stiffness behavior as “Flexible” and 2D behavior as “Axisymmetric” for the 2D tire cross-section and the line bodies (used for rebar modeling)

And for rigid bodies the stiffness behavior as “Rigid” and 2D behavior as “Plane Stress” because rigid bodies are not supported with “Axisymmetric” 2D behavior.

3.2.1.7 Creating the contact pairs

The contact pair between the tire and the rigid rim surface was created and set this contact type as bonded. The contact pair between the tire and the rigid road surface was created.

This contact pair does not take part in the 2D analyses; however it was created in the 2D model and automatically transferred to the 3D model during Map 2d to 3d process.

3.2.1.8 Meshing the 2D axisymmetric tire model

As seen in Fig. 3.4.b, the even-spaced tire model is intended to simulate tire rolling as the tire crown interacts with the rigid road during rotation. The nodes are evenly spaced along the tire edges, and each tire's circumferential edge is given 360 nodes.

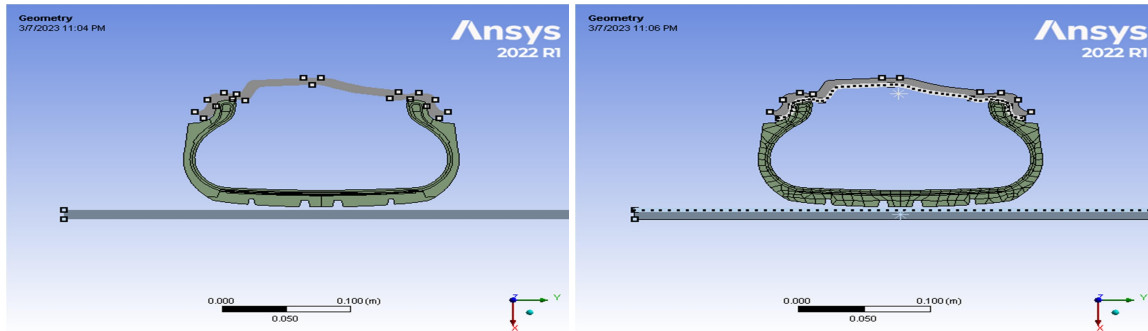


Figure: 3.4: FE 2d tire meshing

For the solid components of the rim, tire body, sidewall, tread, and bead, the element type C3D8R was chosen. C3D8R is an eight-node linear brick, three-dimensional solid element with hourglass control and reduced integration. C3D6R is a reduced integration, 6-node linear triangular prism in three dimensions. Hexahedrons (C3D8R) can sometimes struggle to completely mesh with complex geometries; as a result, wedge and tetrahedral elements (C3D6R) are required. For the belt and carcass shell elements, the S4R element type is chosen. A 4-node, quadrilateral, 3D shell element with large-strain formulation and reduced integration is called S4R.

The element number, nodes and surface area of the even-spaced tire models are summarized in Table 3.5.

Table 3.5: Element number and type of the uneven-spaced tire model

Part	Element Number	Node number	Minimum surface area (m ²)
Rim	51	102	1.8469e-003
Sidewall	47	84	1.38E-03
Tread	51	85	1.72E-03
Belt2	40	82	1.64E-04
Belt1	2	8	1.51E-04
Bead	6	14	9.87E-05
Bodyply_Rebars	78	150	8.3512e-004
Inner Liner	56	110	7.1424e-004
Apex	10	18	1.22E-04

3.2.1.9 Creating Remote Point

The “Create_Remote_Point” object in ANSYS 2022R1 performs the following things for aselected contact pair/connection

- 1) A remote point was assigned to the selected contact pair of tire –rim and tire- road. Theremote point can govern the motion of the rigid surface of the selected contact pair.
- 2) It internally converts the selected mechanical contact pair to an equivalent contact pair of MAPDL by deleting the Mass21 elements & the duplicate set of Target169 elements
- 3) Tabular Friction Coefficient was defined for the selected contact pair/connection.

3.2.1.10 Creating Rebar Elements for belt1 and belt 2 of the tire

The Mesh Independent method was selected in the workbench as Rebar Creation Method. Because this method creates smeared rebar elements at the locations where the line mesh intersects with the base mesh. In order to use this method, you should have the line bodies (representing the rebar locations) meshed with BEAM elements. This object internally converts BEAM elements into Mesh200 elements and create the smeared rebar elements wherever these Mesh200 elements intersect with the base mesh. The material properties for rebar elements will be same as those defined for the line bodies (used in this object).

Rebar properties are defined separately in this object

3.2.1.11 Loading and BCs on Remote Points

2D axisymmetric analysis was performed in two load steps.

In the first load step, rim mounting was performed by applying displacement loading/constraints on the remote point of the Tire-Rim contact pair. The remote point of the Tire-Road contact pair is also constrained in all degrees of freedom, as this contact pair only takes part in the 3D analyses.

In the second load step, inflation pressure was applied on the inner edges of the 2D tire model. The “Remote_Displacement_Loading” object in mechanical workbench was used to apply the displacement constraints on a selected remote point. It was used for both Tire-Rim & Tire-Road connection’s remote points (which were created earlier with the help of the “Create_Remote_Point” object).

3.2.1.12 Map2dto3d_Analysis

Map2dto3d_Analysis helps to convert the 2D tire model into the 3D tire model (including converting contact pairs, transferring loading, BCs & solution items) and perform the rebalancing. The settings for the 3D mesh (which is created by extruding the 2D mesh) was define by 36 number of elements in the hoop direction, Spacing Ratio as 3 and Angle for Mesh Refinement as 40 °.Relatively finer mesh was created in contact with the road.

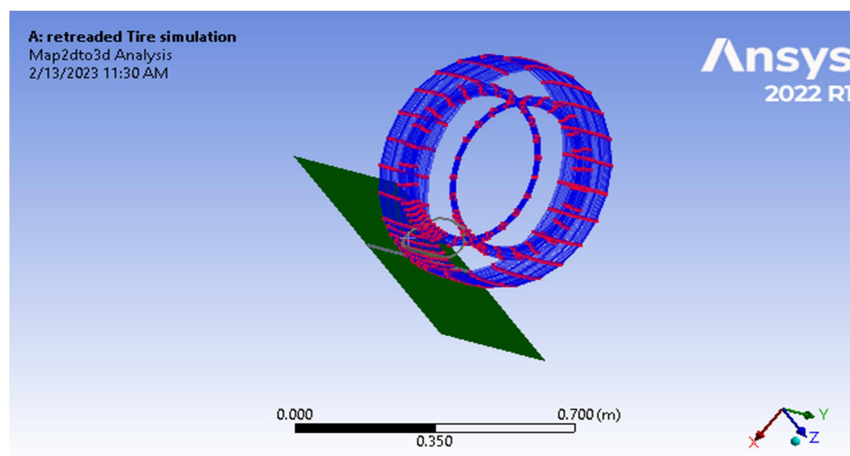


Figure 3.5: FE 2d to 3d mapping

3.2.1.13 Footprint Analysis on the 3D model

After converting the 2D model into the 3D model (Map2dto3d analysis), a footprint analysis was performed on the 3D tire model. It was performed in three load steps.

Load Step1: Contact between the road and the tire was established (through the remote point)

Load Step2: 3000N Vehicle load was applied (through the remote point of the tire-road contact pair)

Load Step3: 1° camber angle was defined (by rotating the rigid road surface)

3.2.1.14 Tire model validation tests

Static load-deflection test was performed to confirm the vertical stiffness of the tire. The purpose of the load-deflection tests was to calculate the tire's steady-state vertical deflection under various loads up to 40 kN. In each loading scenario, the tire was inflated to its recommended pressure of 240 kPa before the previously mentioned vertical load was applied.

As an illustration, Figure 3.6(a) shows the variations in tire deflection response associated with the nominal load of 26.7 kN applied in a ramp fashion, and Figure 3.6(b) displays the deformed shape of the tire following application of the load.

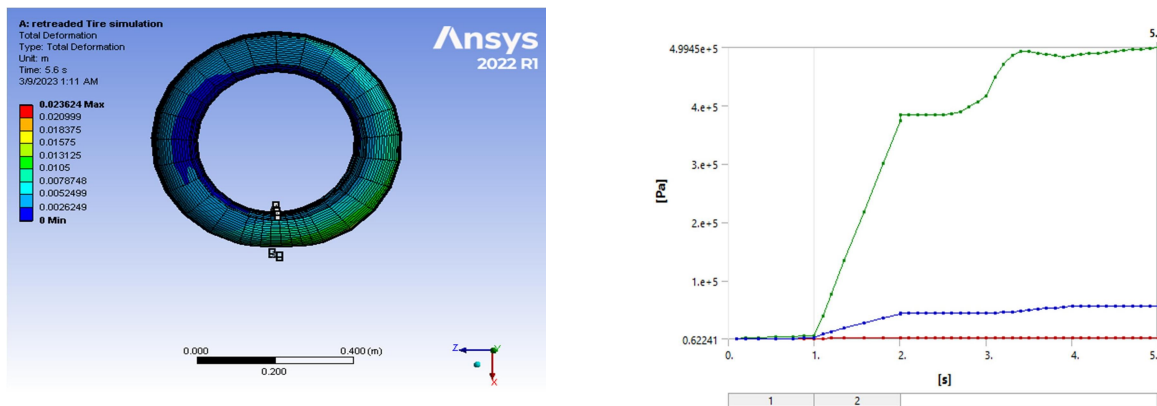


Figure 3.6 (a) Time history of the tire deflection under 3000N vertical load; and (b) Deformed shape of the tire after application of vertical load



Figure 3.7: Testing retread tire deformation under vertical load

Table 3.6-deflection of retreaded tire under physical test vs simulation in response to vertical load

Measured Force (N)	Displacement of retreaded tire under testing (mm)	Finite Element Tire Model Displacement (mm)
0	0	0
150	2.58	2.41
300	5.41	4.946
600	8.51	7.908
800	11.32	10.21
1000	13.9	12.81
1300	16.84	15.72
1500	19.38	18.24

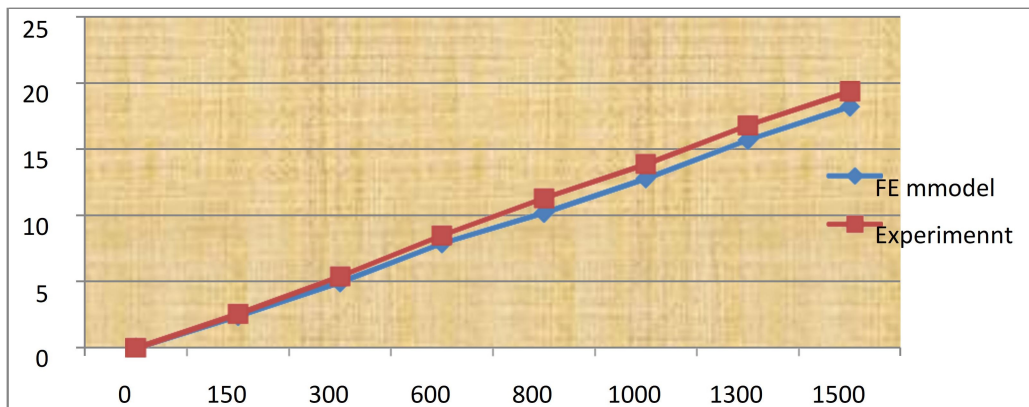


Figure 3.8: deflection of retreaded tire under physical test vs simulation in response to vertical load

Comparison of load-deflection curves discovered experimentally and numerically serves as the primary verification of the selected modeling strategy. Since only the circumferential grooves are modeled and linear elements are used, the FE model is stiffer than the actual tire, as might be anticipated. The analysis results are thought to be in good agreement with the experimental ones, taking into account all introduced assumptions as well as the fact that the measuring apparatus used was not very accurate.

3.2.2 On Vehicle Wear Test Methodology

This section provides a thorough explanation of the tread wear experiments that were carried out at three distinct projects. The testing tools, the experimentation process, and the anticipated results are all covered. The tires used in this experiment were TRIANGLE 7.50R15LT, which are the same size but have a slightly different tread design from the retread tires.

3.2.2.1 Description of the tests methods used

- For the tire wear test procedure, a thorough experimental design and an efficient RP 230A-compliant test protocol was used.
- The various geographical regions of the nation were taken into consideration when choosing test locations and test vehicles.
- The test data were collected per experimental design and test protocol, which were transmitted on a schedule using the provided test data sheet.

3.2.2.2 Description of the tests conditions

The study's plan was created to adhere to Recommended Practice (RP) 203A, Test Tire Procedures for Tread Wear, Serviceability, and Fuel Economy.

To guarantee adherence to the RP 203A test protocol, a special procedure was independently created. The process was adjusted in subsequent meetings with staff so that it was properly in line with best practices (for example, measuring tread depth every 5,000 km rather than waiting for the specified 30,000 or 50,000 KM service intervals). The Appendix contains the final step of the process.

According to RP 203A, a test population per study tire should include at least 30 tires that

have made it to the end of the experiment in order to produce a statistically significant result. We chose 24 tires for this study—12 of each type—under the presumption that some number of them wouldn't survive. Six pickup trucks were used as test vehicles across three different road construction projects, namely the Awash-Dulecha Road Construction Project, the Jinka-Mender Road Construction Project, and the Wolkite Road Construction Project. After being marked with a special serial number, tires were then randomly assigned to the chosen projects. To prevent the potential confounding effects of position and truck assignment on measured performance, retread and new tires are equally distributed and installed on each vehicle's front and rear wheels. Most importantly, it made sure that there would be no unintentional bias in the experiment's results.

3.2.2.3 Experimental Setup

This was done to make sure that all test tires were mounted uniformly and that everyone who would be gathering and recording data on tread depth was knowledgeable about how to do so. Prior to installation, selected tires were inspected. The ability to measure tread depths was taught to service personnel.

3.2.2.4 Data Acquisition

The average of 10 tread depth measurements taken on each test tire when vehicles were brought in for routine maintenance is represented by each data point.

Five tread depth readings were taken at the valve stem's location, and five more were taken 180 degrees away (i.e. halfway around the tire's circumference on the opposite side).

To make sure the tires were mounted on the designated test vehicle properly, each tire underwent a visual inspection. Pictures of failed tires from the testing were given to support the documentation procedure.

In any case, there will inevitably be a number of surface changes that necessitate characterizing the typical road surface structure, i.e., the sharpness and coarseness of the road surface, which are likely to have a significant impact on the abrasion loss. Although the average structure may vary between test routes, the difference between the two averages is already most likely to be less than the variations found along each route individually.

Additionally, it's likely that the average of a test route will represent the average for the entire geographic area.

Wear results are always averages because they are typically gathered over a period of time. If the ranking of test compounds is not significantly impacted, this is not too serious.

3.2.3 Methodology for problem Identification

The methodology adopted for this work began with the selection of the tire retreading process, i.e., cold retreading process. Further, data has been collected over a period of six months from the corporation. During the data collection phase, the information regarding various types of tire defects and other important factors that play significant roles in the assuring the quality and performance of retread tires have been collected. The various defects that occur in the retreaded tire are identified in the next step and a Pareto chart has been prepared to depict the severity of defects. Using the output of the Pareto chart the most severe defects are identified. Finally, possible appropriate solutions to overcome the defects are prepared through literature review to improve the quality, safety, durability, and performance of retreaded tire.

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 Simulation Result

4.1.1 Equivalent Stress (Von-Mises Stress)

Studies were done at three different normal load cases: 3000N, 4000N and 5000N in order to understand the effect of the changes in normal load on the equivalent stress distribution shown on figures 4.1-4.3. Studies were also conducted with three different inflation pressures: 2.5bar, 3.5 bar and 4.5 bar, in order to study the effect of changes in inflation pressure on the equivalent stress shown on figures 4.1, 4.4 and 4.5.

On comparing the two types of tires on figures 4.1-4.3, with increase of the load but the same internal pressure, we can see that the stress distribution and the peak stress levels in retread tire and new tire are quite comparable. As seen from the figures, increasing the normal load from 3KN to 4KN, the maximum stress also increased almost in a linear fashion. The maximum stress found in the tread area as expected on both tires but when the load increases from 4 KN to 5 KN, the maximum stress on the tread decreases while the stress on the side wall of both tires increases. However it's quite evident from figures that the distribution of stresses across the tire is not exactly the same in both cases. Particularly on figure 6.3 when the load is 5000N with the same internal pressure of 2.5 bar, the side wall is also one of the area of retread tire which suffer from maximum stress compared with new tire. The reason for this condition might be because of the old tire lost its stiffness behavior a little bit or it might also be because of inaccurate material properties of old tire in the simulation process. Another thing to notice is that the stresses are generally higher in the tire shoulders than on the center. This might be because of the camber angle given in the simulation set up.

On the hand with increase of internal pressure from 2.5 bar to 4.5 bar with the same normal load of 3000 N, the maximum stress significantly increased on both tire with pick value of for 0.84 MPa new tire and 0.83 MPa for retread tire which occurs on the shoulder. The tread and the side wall in this case experience lower stress relatively.

Given that the stresses are distributed where the greatest deformation occurs, the distribution of the stresses makes sense. If the model is run without taking into account the

ground plate, the pneumatic pressure would cause the stress to be distributed evenly at a given width over the circumference of the tire. The tread as a whole will experience the highest stresses at its narrowest points when compressed by the plate. The highest stresses are present in the shoulder of the tire for this reason.

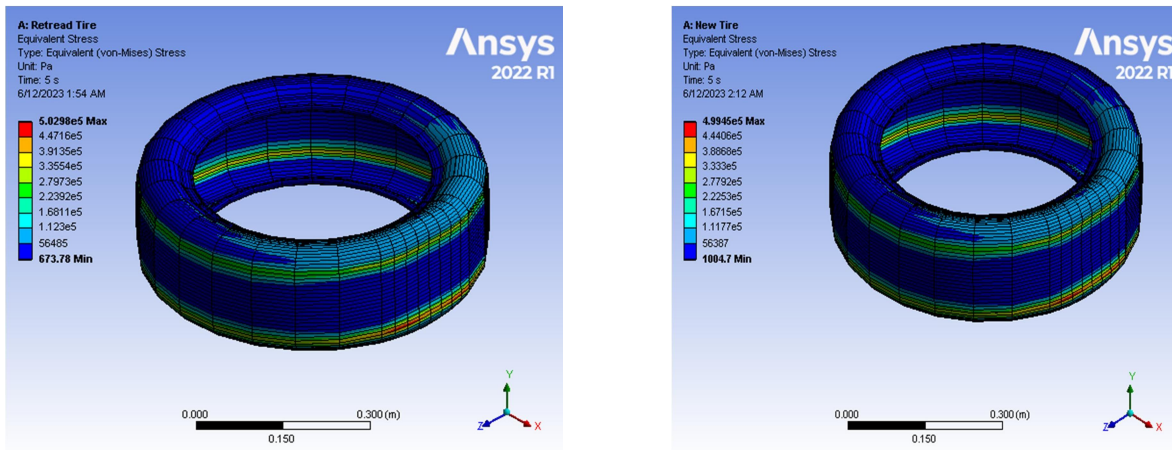


Figure 4.1: Equivalent von-mises stress distribution of retread tire and new tire at 2.5 bar and 3000N

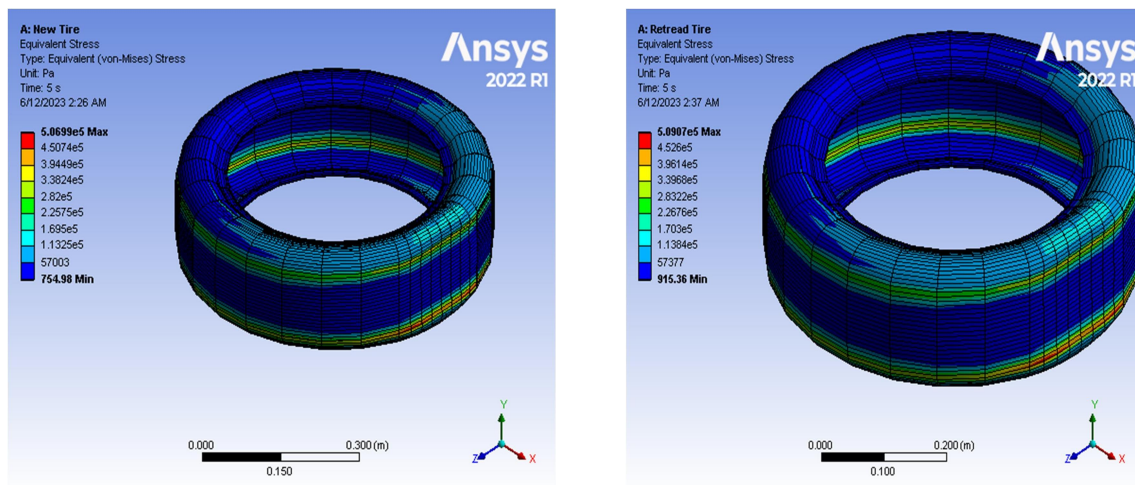


Figure 4.2: Equivalent von-mises stress distribution of retread tire and new tire at 2.5 bar and 4000N

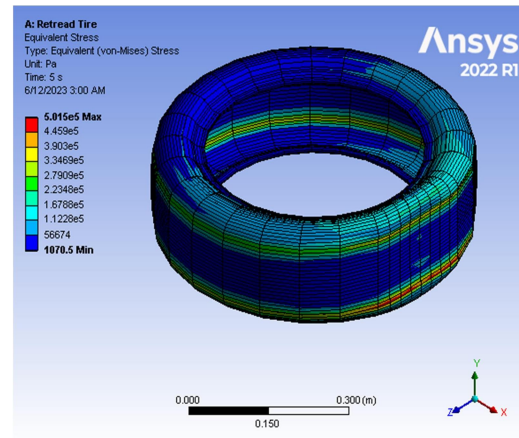
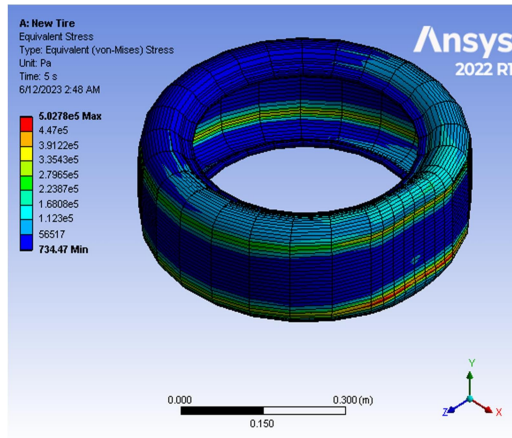


Figure 4.3: Equivalent von-mises stress distribution of retread tire and new tire at 2.5 bar and 5000N

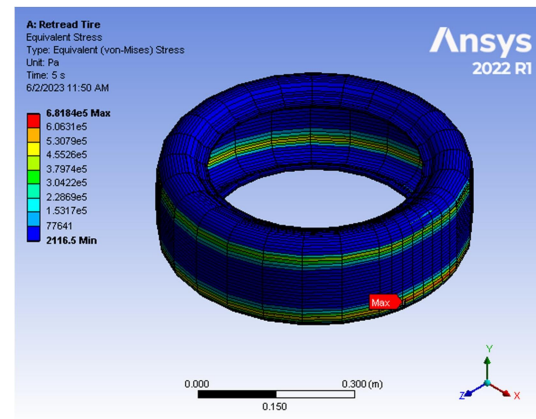
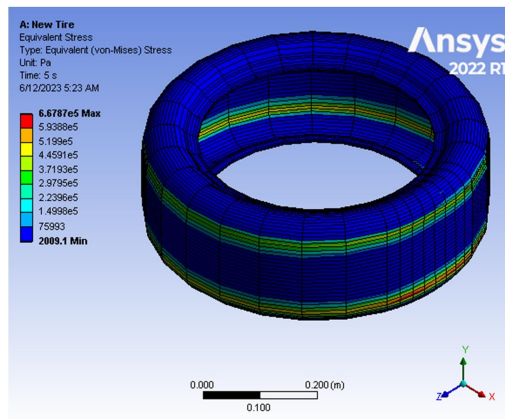


Figure 4.4: Equivalent von-mises stress distribution of retread tire and new tire at 3.5 bar and 3000N

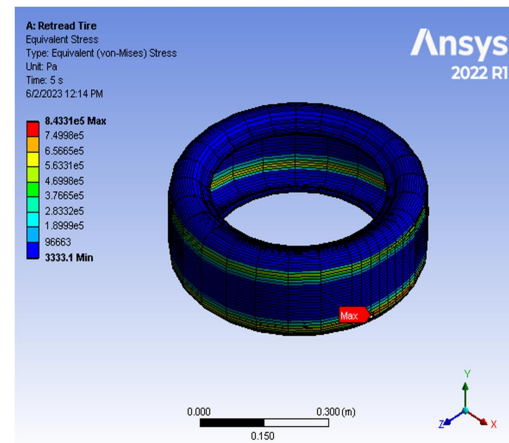
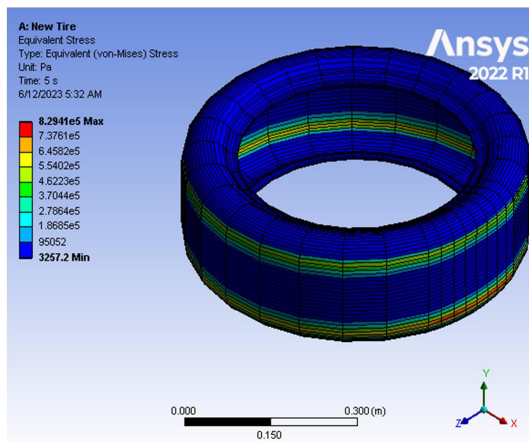


Figure 4.5: Equivalent von-mises stress distribution of retread tire and new tire at 4.5 bar and 3000N

It can be seen from the Figures above that the stress distribution in the tread ranges from 0.97 to 4.25 MPa, and the maximum stress value of 0.5015 to 0.50907 MPa and 0.499 to 0.50699 MPa for retread and new tire respectively occurs at the shoulder, gradually decreases toward the center of the ground contact along the width direction, and then becomes larger when approaching the side wall of both tires.

But with increase in internal pressure the maximum stress value of 1.65MPa occurs at the edge of the tread, and the stress gradually decreases in the width direction toward the ground contact center.

4.1.2 Total Deformation

The deformation was as depicted in the following figures when the methodology's inputs were used. Two external factors—the external load and the pressure applied from the inside that simulates air pressure—have an impact on the deformation. The rubber properties are effectively preventing the tire structure from elongating and rounding out. The overall deformation under the additional stress caused by the displacement of the ground plate appears realistic. With the increase of internal pressure from 2.5 bar to 4.5 bar while keeping the normal load 3000 N, both new and retread tire react in the same way that the maximum deflection decrease linearly on the same fashion. The highest deformations happen close to the contact area and with a maximum deformation for new tire is 15, 12, 10 mm and 16, 11, 9 mm for retread tire with internal pressure increment of 2.5, 3.5 and 4.5 bar respectively.

On the other hand with increase of normal load from 3000N to 5000 N while keeping the internal pressure 2.5 bar, the maximum deflection of both tire increase but the rate of deflection for retread tire is quite higher than that of new tire. The figures below also show how smoothly the transitions between the colors are with no sharp edges. This indicates that the solution has converged fully and has a satisfying mesh density. For comparison purpose experiment of actual retread tire deflection was done on the bench with the same internal pressure of 2.5 bar and 5000 N external load and maximum total deformation of 16 mm doesn't seem too far off from realistic values. The retread tire in this simulation has a realistic deformation caused by both internal and external pressure forces

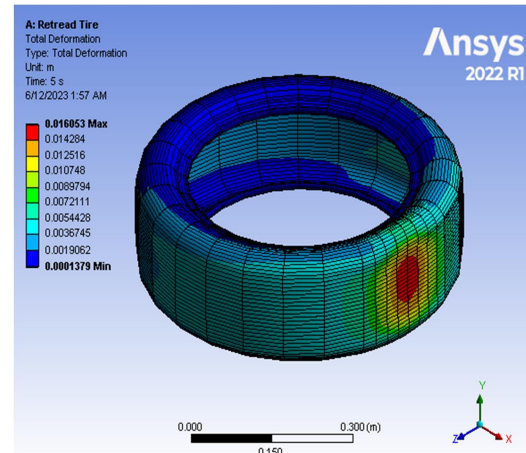
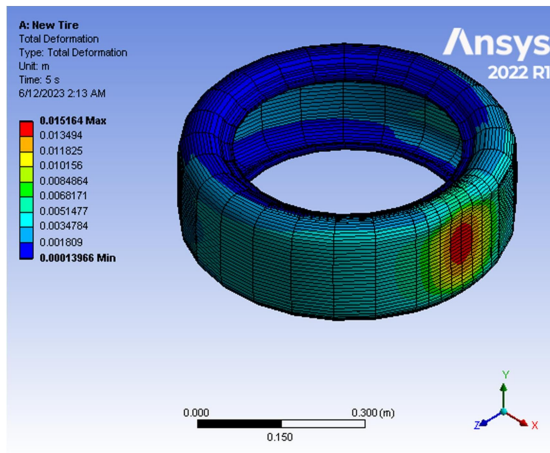


Figure 4.6: Total deformation of retread tire and new tire at 2.5 bar and 3000N

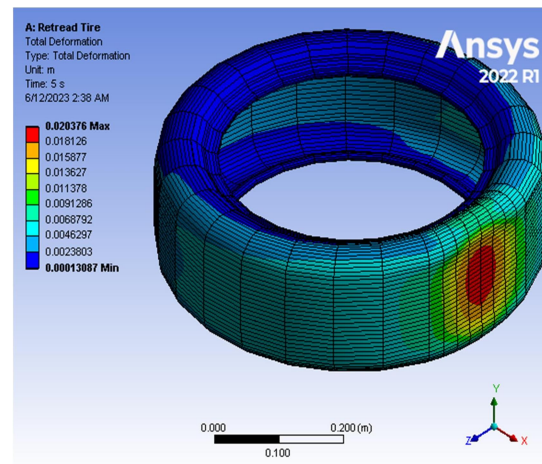
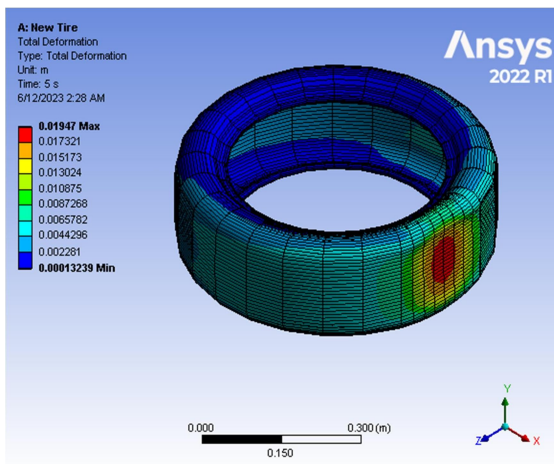


Figure 4.7: Total deformation of retread tire and new tire at 2.5 bar and 4000N

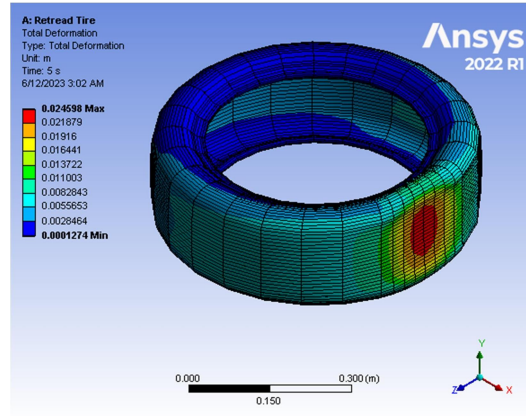
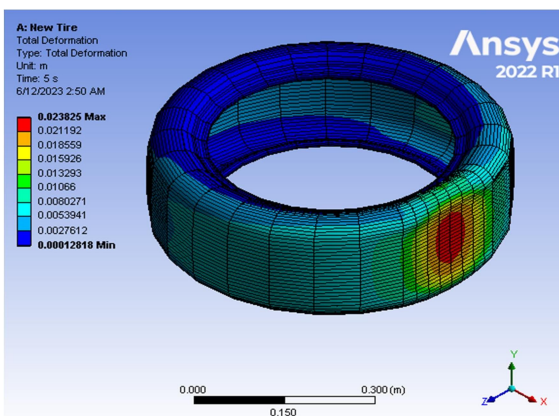


Figure 4.8: Total deformation of retread tire and new tire at 2.5 bar and 5000N

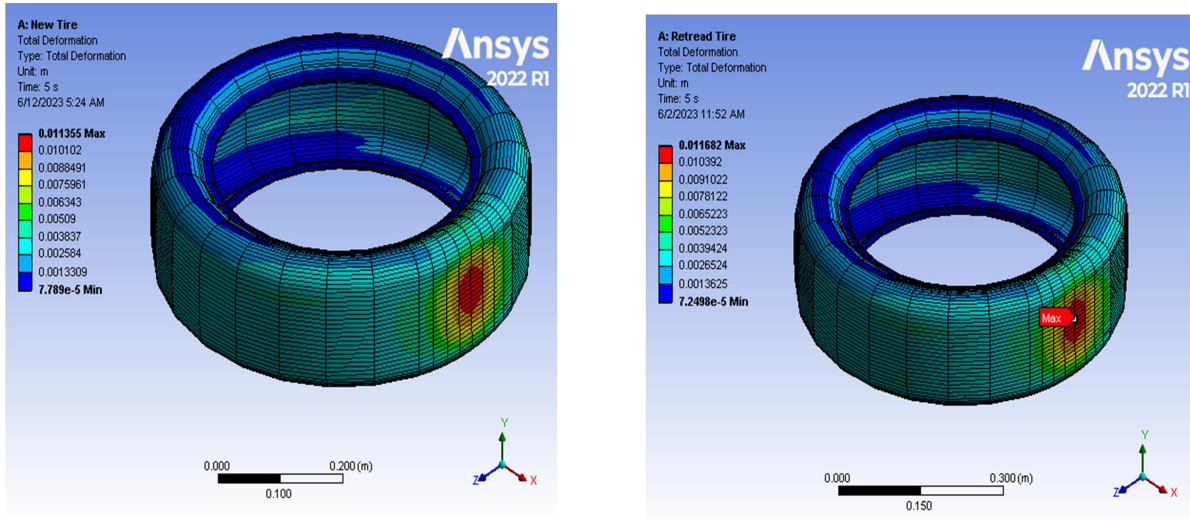


Figure 4.9: Total deformation of retread tire and new tire at 3.5 bar and 3000N

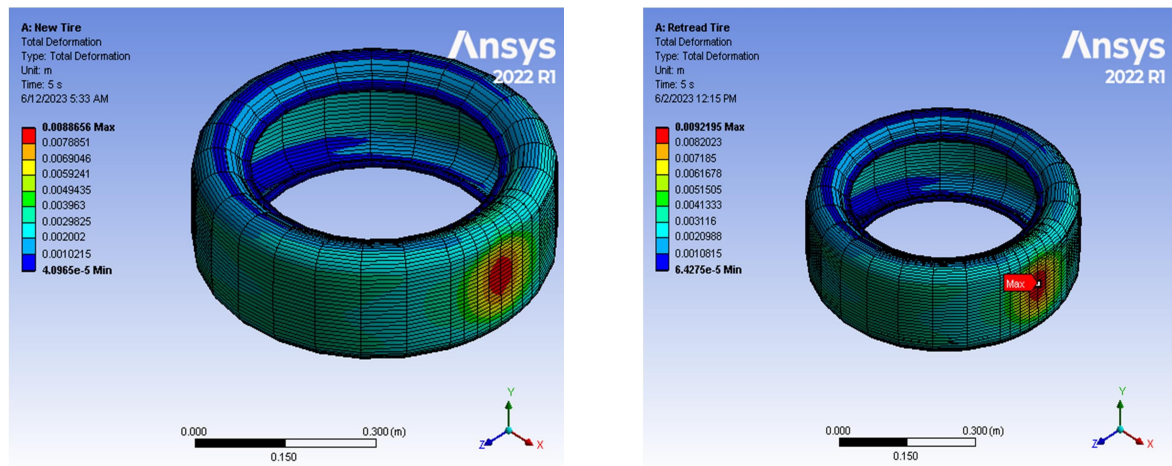


Figure 4.10: Total deformation of retread tire and new tire at 4.5 bar and 3000N

Table 4.1: Total Deformation response of new and retread tire for pressure and load variation

Force	Inflation pressure	Total deformation of retread tire		Total deformation of new tire	
		Minimum	Maximum	Minimum	Maximum
3000N	2.5bar	1.379e-004 m	1.6053e-002 m	1.3966e-004 m	1.5164e-002 m
4000N		1.3087e-004 m	2.0376e-002 m	1.2818e-004 m	1.947e-002 m
5000N		1.274e-004 m	2.4598e-002 m	9.5554e-003 m	2.3825e-002 m
3000N	2.5 bar	1.379e-004 m	1.6053e-002 m	1.3966e-004 m	1.5164e-002 m
	3.5 bar	7.2498e-005 m	1.1682e-002 m	7.789e-005 m	1.1355e-002 m
	4.5 bar	6.4275e-005 m	0.92195e-002 m	4.0965e-005 m	8.8656e-003 m

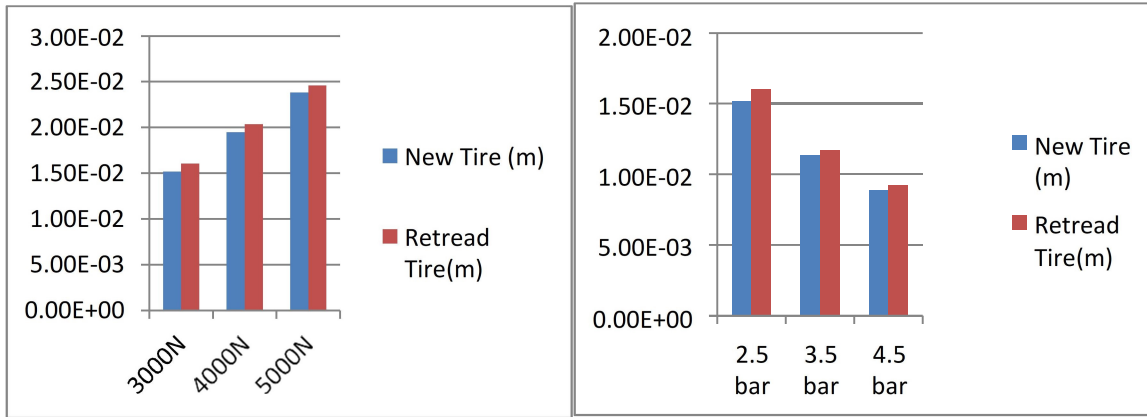


Figure 4.11: Total deformation comparison of new tire vs retread tire

4.1.3 Contact Area

The deformation, contact area, and pressure distribution of the tire at the tire-road interface directly affect a vehicle's traction, braking, ride quality, and pavement loading characteristics. However, these characteristics also depend on the tire's structural characteristics and inflation pressure (Xiong Zhang, 2001). The contact area results of the new tire and retread tire from the finite element simulation results are discussed in this section as follow.

To investigate the impact of variations in inflation pressure on the contact area characteristics, study were conducted at three different inflation pressures: 2.5 bar, 3.5 bar, and 4.5 bar. To better understand the impact of variations in normal load on the contact area, studies with three different normal load cases—3000N, 4000N, and 5000N—were also carried out while maintaining an internal pressure of 2.5 bar.

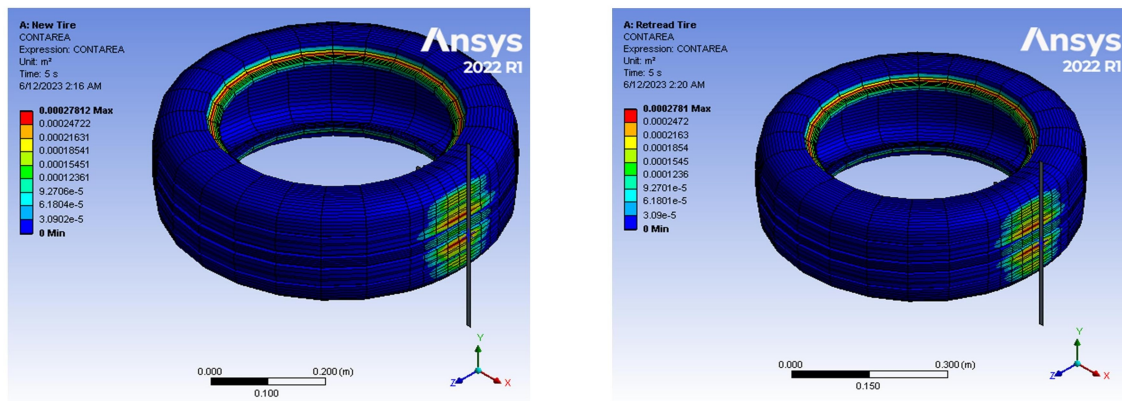


Figure 4.12: Contact area of retread tire and new tire at 2.5 bar and 3000N

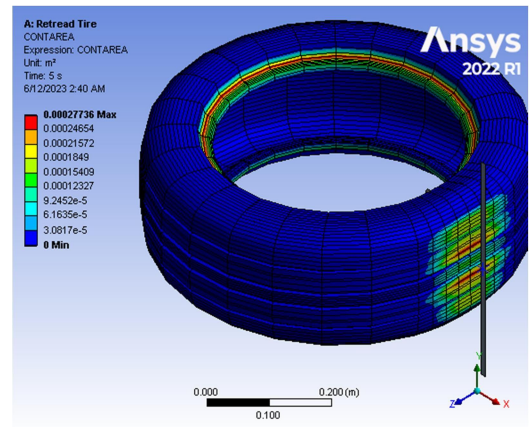
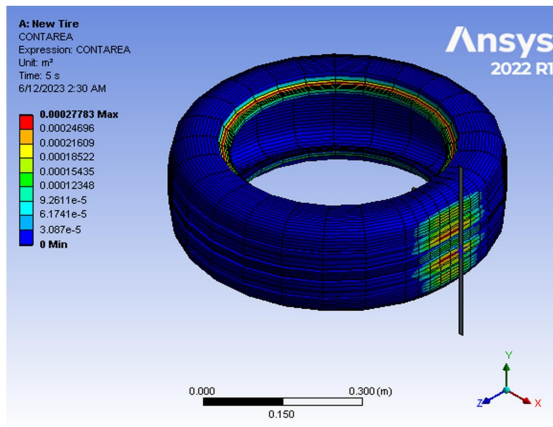


Figure 4.13: Contact area of retread tire and new tire at 2.5 bar and 4000N

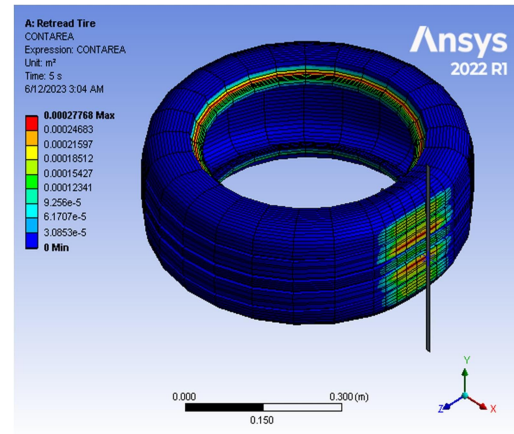
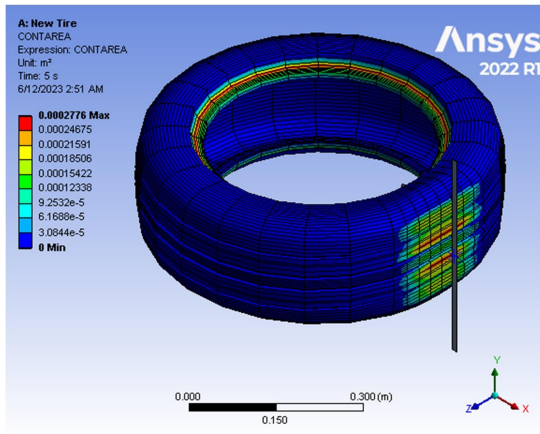


Figure 4.14: Contact area of retread tire and new tire at 2.5 bar and 5000N

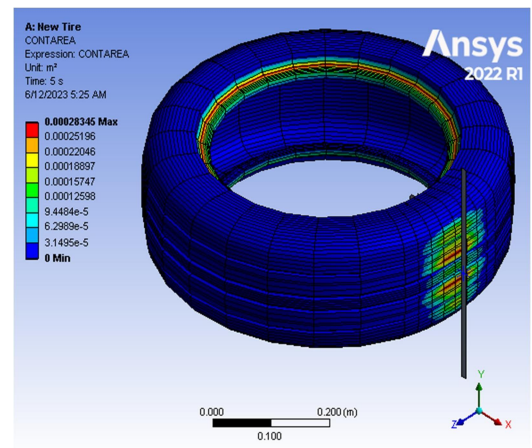
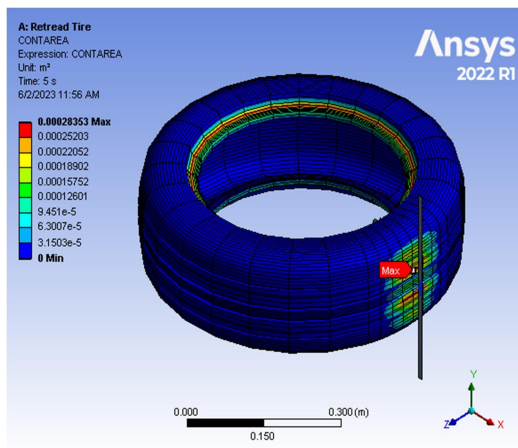


Figure 4.15: Contact area of retread tire and new tire at 3.5 bar and 3000N

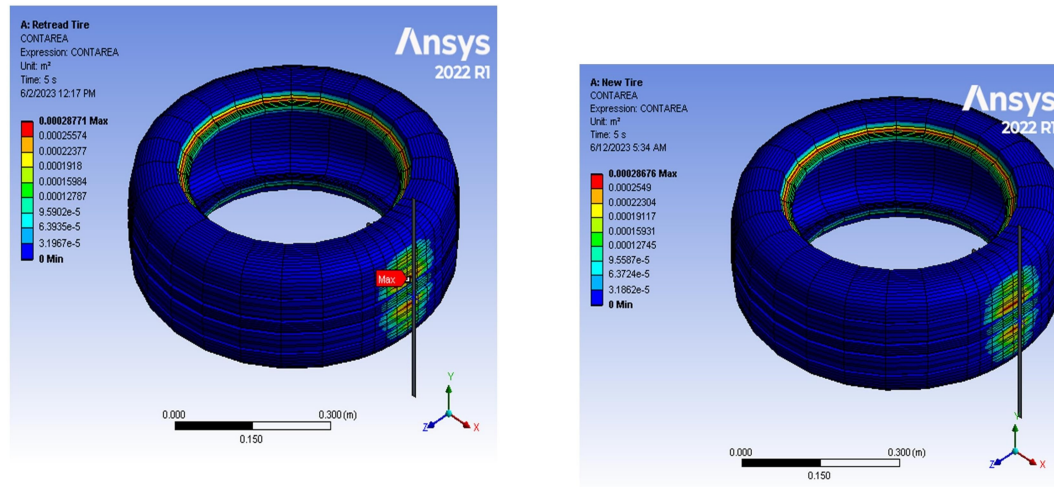


Figure 4.16: Contact area of retread tire and new tire at 4.5 bar and 3000N

Table 4.2: Contact Area of new and retread tire for pressure and load variation

Force	Inflation pressure	Contact area of retread tire	Contact area of new tire
3000N	2.5bar	8.754e-002 m ²	8.6599e-002 m ²
4000N		8.9776e-002 m ²	8.9424e-002 m ²
5000N		9.3519e-002 m ²	9.2946e-002 m ²
3000N	2.5 bar	8.754e-002 m ²	8.6599e-002 m ²
	3.5 bar	8.4039e-002 m ²	8.3767e-002 m ²
	4.5 bar	8.2987e-002 m ²	8.2701e-002 m ²

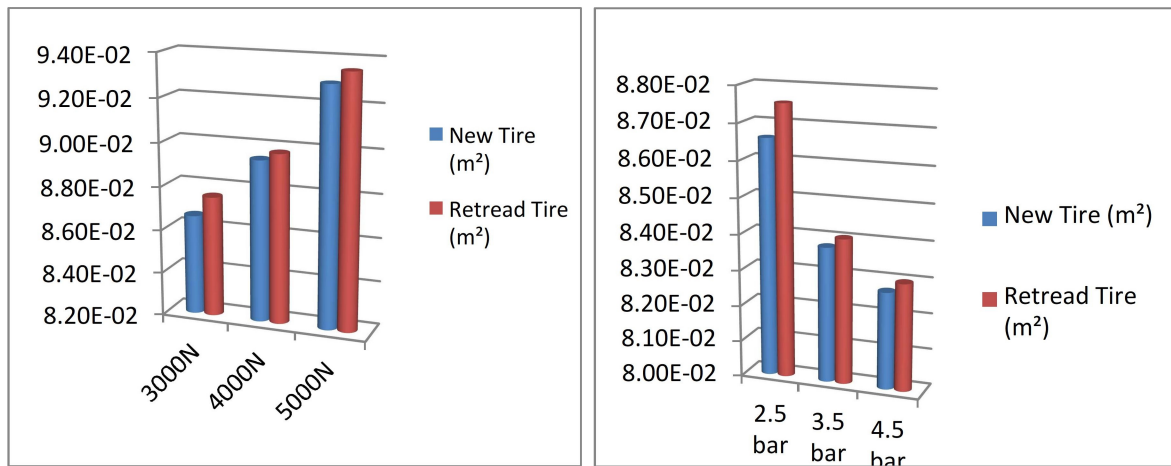


Figure 4.17: Contact area comparison of new tire vs retread tire

The footprint shape and size of a new tire and one that has been retread appear to be

reasonably comparable to one another in figures 4.12 to 4.16. Figure 4.17 shows that increasing the normal load significantly increased the footprint area. As a result of increasing the load from 3 kN to 5 kN, it was discovered that the percentage increase in overall contact area was approximately 6.7% for new tires and 7% for retread tires. The figure also demonstrates how raising the inflation pressure significantly reduced the contact patch areas on both tires. For the same normal load, the footprint area has shrunk by 4.5% for new tires and 5.2% for retreads. Lowering the inflation pressure would imply a change in the pre-tensioned state of the tire. According to (Pottinger, 2005), the tire has a double curvature that extends in both the circumferential and lateral directions. Decreased inflation pressure would alter the general shape of the tire because the pre-tensioned state of the tire would have changed. This implies that the stiffness of the tire as a whole varies. The sidewall stiffness would be lower and the deflection would be higher, which would result in a smaller loaded radius for the tire.

Due to the increased contact area and tire's capacity to deform over uneven surfaces, low tire pressure can improve traction. For everyday driving, it is not advised to have a too low tire pressure because this increases edge wear and speeds up heat generation, which increases the risk of the tire cracking (R. V. D. Steen, 2010).

On the contrary, as we can see on figure 4.17, b, with increase of normal load with the same internal pressure, both tires' contact area increase as expected but above 4000N the retread tire contact area increases 30% as compared with new tire which increases by only 20%.

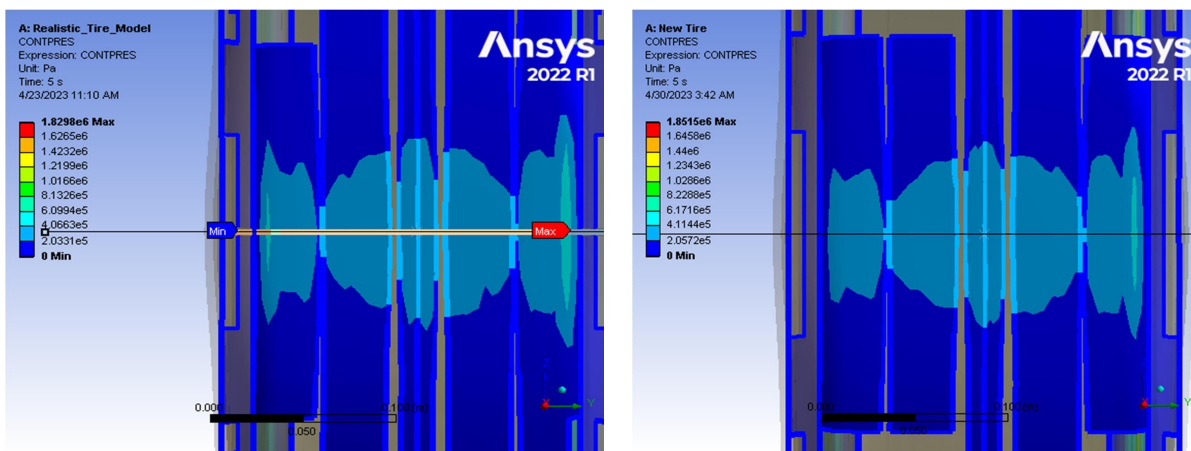


Figure 4.18: Ground pressure response of new tire vs retread tire under normal load of 5000N and Under tire pressure of 2.5 bar and a load of 5 kN, the grounding pressure distribution of both

new and retreaded tires is shown in Fig. 4.18. The figure demonstrates how much lower the ground contact pressure is on both tires. This area has low pressure values, which gradually rise toward the shoulder from the light blue region. The higher contact pressure zones are evidently situated fairly close to the shoulders of both tires. The contact pressures in the center region are relatively lower than those in the shoulders.

This is quite characteristic of a passenger car tire as discussed by (Pottinger, 2005). A lower contact pressure with the ground results in better performance for a vehicle's mobility on any terrain (TIBERIU GIURGIU1, et al., 2016). The average pressure over the middle area is not very high, with both tires having pressures lower than 0.4 MPa. There are two locations on both sides of the tires where the pressure is higher than 0.6 MPa, right below the sidewall's termination. The grounding pressure of the retread tire shoulder is slightly higher than that of the new tire, despite the fact that the pressure distribution of the two tires is almost the same in the grounding area (Figure 4.18). The minimum pressure value increases along the tire's width at a different rate from the grounding center than it does on a new tire. This suggests that there is a higher likelihood of wear and tear on the tire shoulder.

4.2 Experimental Test Result

The capacity of a tire to travel long distances determines its wear performance. Consider the tire service life, which is the number of miles after which a point on the tread has reached the legal limit of the wear indicator, as one method of assessing wear performance. The mass loss from the tread, which is typically expressed in grams per hundred kilometers, and the transverse worn profile, which allows the wear shape of the tread to be qualified, both affect how long a tire will last in service. The conditions under which a tire is used, including the type of driver and the location, determine how long it will last., which gives designer to modification tire force applied on tire or changes in rubber or ground surface (Olivier et al., 1998).

The main goal of this experiment was to compare the performance of new tires and recaps in "real world duty cycle" environments and to gather data on the cost effectiveness of using retread tires versus new tires.

I. Study of Tire Removal because of early damage

The number of tires that were removed from service due to early damage is shown in Table

4.4. There were three different codes for tire removals. The tires were removed because of tread separation, excessive wear, and irregular wear.

Table 4.4 No. of tires removed from the study by early damage

List of failure reason	New tire	Retreaded tire
Excessive wear	0	1
Tread separation	0	1
Irregular wear	1	2
Total number	1	4

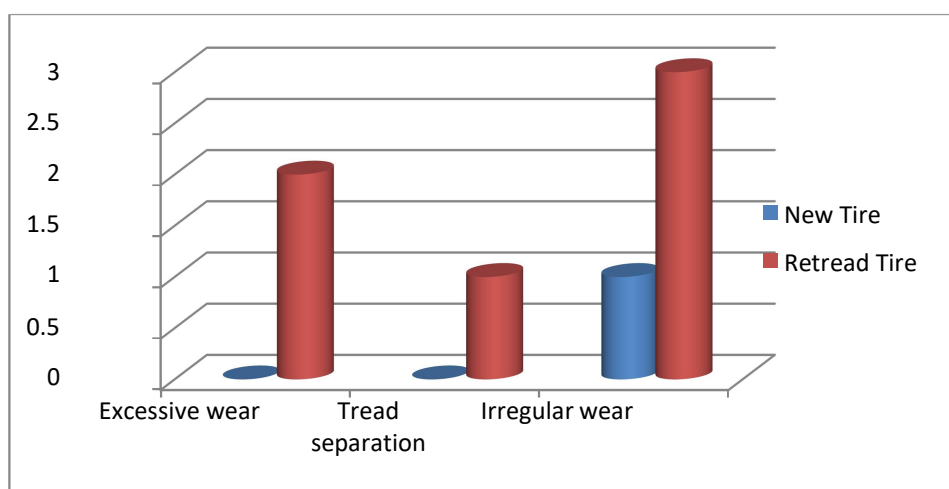


Figure 4.19: Tires removed from the study because of early damage

a) Excessive Wear

Excessive wear means when the tire tread depth reaches either at or near the 4/32nd inch safety threshold very early (business.Michelinman.com). From table 4.4 excessive wear was shown on only one retread tire with a bulge or excessive wear in the tread area.

Excessive wear on new tires can be brought on by various driving conditions, including steep terrain, frequent and severe turns, abrasive road surfaces, and certain vehicle configurations and features like power steering, heavy axle loads, setback axles, high wheel cuts, short wheel base tractors, and long wheel base straight trucks. Though in this instance only one retread tire showed excessive wear, incorrect retreading technique may have been the true cause of its

failure rather than the previously mentioned service conditions. Excessive wear on retread tires is caused by incorrect skiving or skive filling during the retreading process, which traps air or permits air to seep under the tread and causes a localized loss of adhesion.



Figure 4.20: one of retread tires removed from the study because of excessive wear

b) **Tread Separation**

No new tire was removed by failure related with tread separation but one retread tire was removed which was identified in jinka project with portion of tread rubber only lifted and separated from the buffed surface of the tire body shown below.



Figure 4.21: one of retread tires removed from the study because of tread separation

A common issue with retread tires is tread separation, which is primarily the result of poor retread craftsmanship and/or materials. Other potential causes of tread separation include old

cushion gum or tread rubber, improper cure conditions, missed nail holes, and scorched or contaminated buffed surfaces.

A study by (Woodrooffe et al., 2008) examined 88 casings that had detached in some way; 59 of these casings (67%) were retreads, and 59 of the 88 casings had detached completely.

The likelihood that a disabled tire will disintegrate, that is, complete separate of the tread materials and the belt, increases with the length of time it is left in use due to the increased potential for heat generation and severe structural deflection. Additionally, the study discovered that retreads accounted for 73% of casings that experienced total detachment. The study ultimately came to the conclusion that during the retreading process, air either seeped through or became trapped in the injury and under the tread, which ultimately decreased adhesion between the tread and the tire and caused a separation.

c) Irregular Wear

Tire wear that is uneven or irregular is a major issue the trucking industry facing today. Every tire brand has encountered this unfavorable circumstance.

Two retread tires and one new tire were removed from the study because of irregular wear. one retread tire and one new tire which shown irregular wear were identified on the front wheel of same vehicle in jinka project.

Irregular wear is typically the result of misaligned drive axles or incorrect toe conditions. When there is toe in, the tires on the outside of both steer tires will get worn, and when there is toe out, the tires on the inside of both steer tires will get worn. The inside shoulder of one tire and the outside shoulder of the other steer tire are worn down by drive axle misalignment. The same outcomes may be obtained from improperly maintained suspension parts, such as torque rods, springs, and spring bushings.

In addition to the aforementioned reasons, retread tires may experience irregular wear because of retread processing issues, cure-related issues, and potential belt edge separation.



Figure 4.22: one of new tires removed from the study because of irregular wear

From the above results it can be concluded that failure of retread tires by any reason was higher than new tire although the sample is very small and different conditions that contribute to the tire failure were not considered in this study. In the case of ECWC condition, Even if all retread tires pass different inspection processes before the final use, still there are some limitations in the retreading process that lead to reduce quality. From table 4.4, it is shown that almost 20% of the total retread tires sample were failed and rejected from the study. Early failure of retread tires is attributed to the state of the tire casing rather than the adherence of the new tread, according to (Woodrooffe et al., 2008). Rereading frequently results in casing flaws being missed. As a result, the capacity to examine the tire casing and identify any flaws in it is the primary factor influencing the reliability of retreading. Tire flaws can be buried beneath the tire's components, making it very challenging to find them during a retread inspection. Therefore in general retread tires are cost effective and reduces environmental pollution related with waste tires but immediate failure like tread separation, irregular wear and excessive wear within a short period of time might occur, so from the safety point of view using retread tires for steer wheel is not recommended. Tire failure on steer axles may contribute to vehicle loss of control, according to (Woodrooffe et al., 2008).

Retreaded tires, according to the US Department of Transportation, meet the same quality standards as comparable new tires. However, they can be used anywhere new tires can be used, with the exception of the steer axle of passenger-carrying buses, per Title 49, Part 393.75, Paragraph (D) of the US Federal Motor Carrier Safety Regulations.

I. Study of wear rate

According to Rosen Ivanov (2016), wear is the definition of material removal from a surface that is impacted by frictional interaction with another surface. Tire wear is characterized as a complex phenomenon because it is frequently measured or estimated after a considerable amount of time has passed, during which time the wear process may have been influenced by a number of processes other than sliding friction. These procedures may involve mechanical, physical, or chemical elements, among others.

Wear rate is usually expressed in terms of miles per 32nd inch of worn tread depth. Wear rate can be tracked during tire life and used to calculate projected tire removal mileage. Projected mileage should only be used as a tire performance indicator (Rosen Ivanov, 2016).

Assessment of the tread depth of retread and new tires with their wheel position in every 5000 km were done and Figure 4.23 and 4.24 present the data graphically.

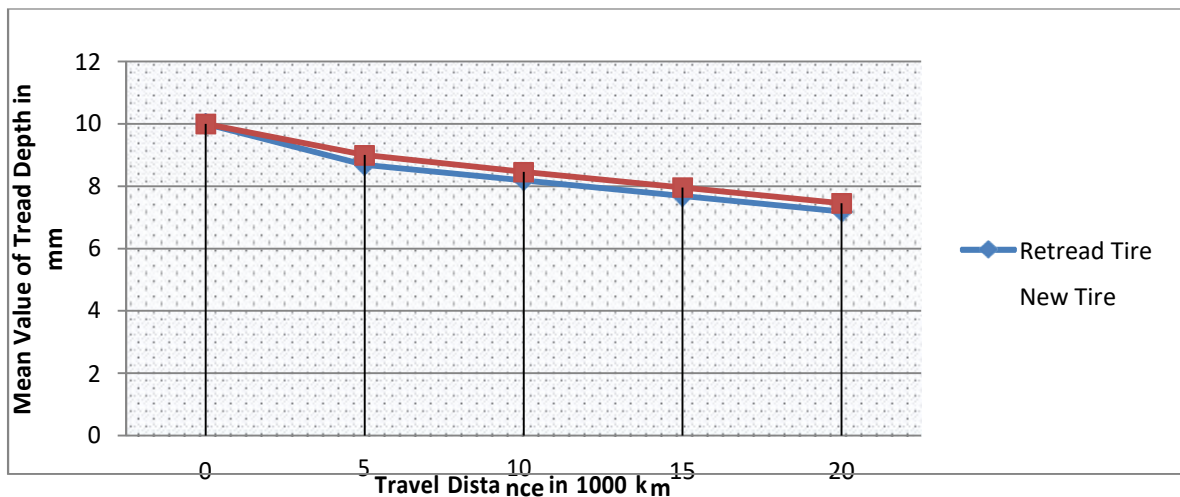


Figure 4.23: Tread Wear in mm for Different Travelling Distance of New and Retread

The above graphs indicate that the tread wear of new and retreaded tires differ for the same travel distance; that is, the new tire has less tread wear than the retreaded tire. With the same travel distance 20,000 km the average wear rate of retread tires is 10.6 % higher than new tires. And comparing steer axel and drive axel tires, wear rate of drive axel tires are higher than new tires as expected but drive axel retread tires average wear rate was 5.3 % higher than steer axle retread tires but only 4.1 % increment in the case of new tires.

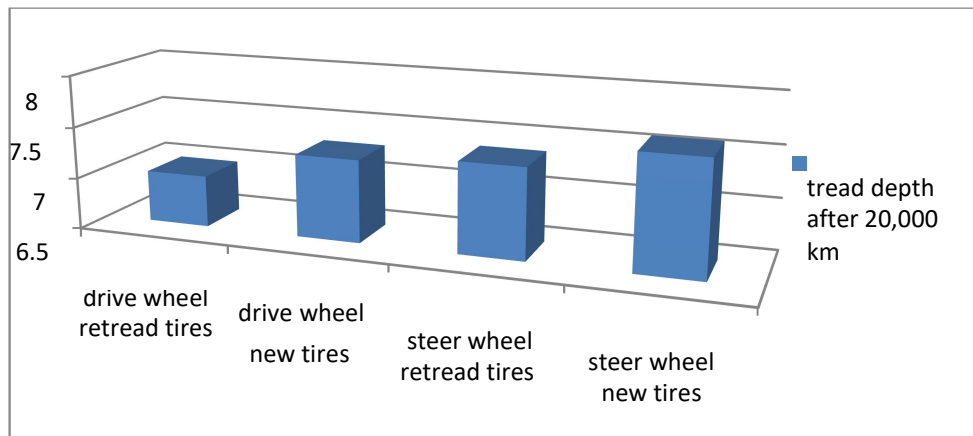


Figure 4.24: wear rate by wheel position after 20,000 km of vehicles travel

II. Study of Mileage

According to Tire and Rim Association (TRA), the minimum tread depth that a tire can be safe for driving must be 1.6 mm or $2/32^{\text{nd}}$ inches and below this braking and vehicle control are impaired. Tires below the minimum tread depth are generally not safe for driving and must be replaced. By projecting the wear rate up to the minimum tread threshold, we can find the total travel distance that a tire can achieve, which is useful tread mileage (UTM). The term UTM refers to the average miles traveled per $1/32^{\text{nd}}$ (i.e., $1/32^{\text{nd}}$ of an inch or 0.793 mm) of tread depth (Deierlein, 1992). It is generally considered that the tires with the highest wear rate (i.e., the most average miles per 32^{nd} rate of wear) will yield the highest total removal mileage.

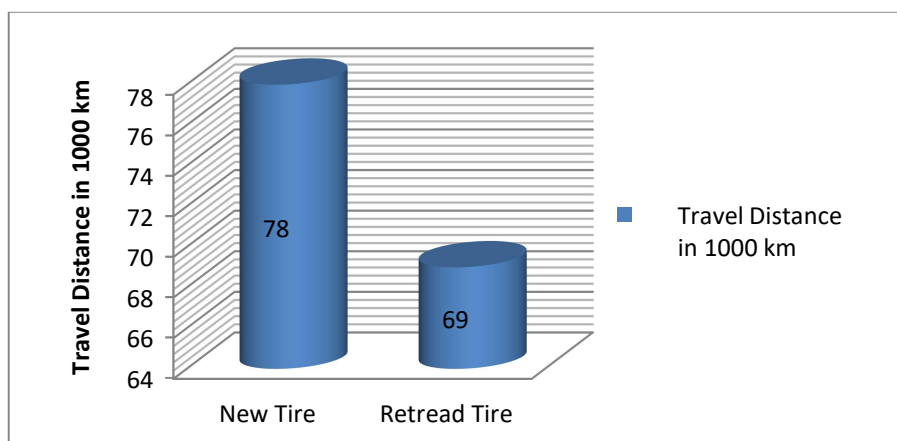


Figure 4.25: Mileage comparison of new vs retread tire

The aforementioned graphs demonstrate how the tread wear of new and retreaded tires differs for the same travel distance—that is, the new tire has less tread wear than the retreaded tire because a new tire's rubber ply has a high wear resistance and is hard. In contrast, the rubber ply of a retreaded tire has less wear resistance and is softer than that of a new tire.

As seen in the above graph the projected average total travel distance of retread tires and new tires will be 69,000km and 78,000 km respectively. This means the average total mile age of new tires is 13 % higher than that of retread tires.

According to their study by (Walid Abdul-Kader & Muhammad S. Haque, 2011), the average life of retread tire is 75 – 100% of new tire. This depends on driving conditions and retread depth

According to (Vankar Bharat et al., 2015), tire retreading conserves rubber raw material because it is primarily composed of approximately 100% rubber, of which 20% is used in tires that are no longer functional and the remaining 80% is tire carcass. They added that the cost of retreading can reach up to 28% of the price of a new tire, but that the life of a retreaded tire is 77% of a new tire. Ultimately, they came to the conclusion that used tires have a longer overall travel distance than new tires and cost less per kilometer. Because we can retread the same tire a number of times.

Retreaded Michelin truck tires, according to Michelin Center of Technologies, Research and Development, can last between 200,000 and 250,000 miles with proper care and driving conditions—more than 80% of the life of a new tire. As such, the result of this study is reliable and representative of current retreaded tires.

Comparing with the other two projects, the average wear rate of tires after 20,000 km of travel in the Awash-Dulecha project is 6 % higher than Jinka and 7% higher than Wolkite project. The reason for this might be the environmental temperature of the project area. Rosen (Rosen Ivanov, 2016) states that the properties of the surface and the surrounding environment have the biggest effects on the total amount of material being transferred. Higher temperatures lead to more adhesive wear in terms of environmental conditions. The process of adhesive wear is accelerated because the bonds that are formed are on the atomic scale and a higher temperature affects the rate of chemical reaction. When two surfaces rub against one another, frictional heat is frequently produced, which raises the temperature (Rosen Ivanov, 2016).

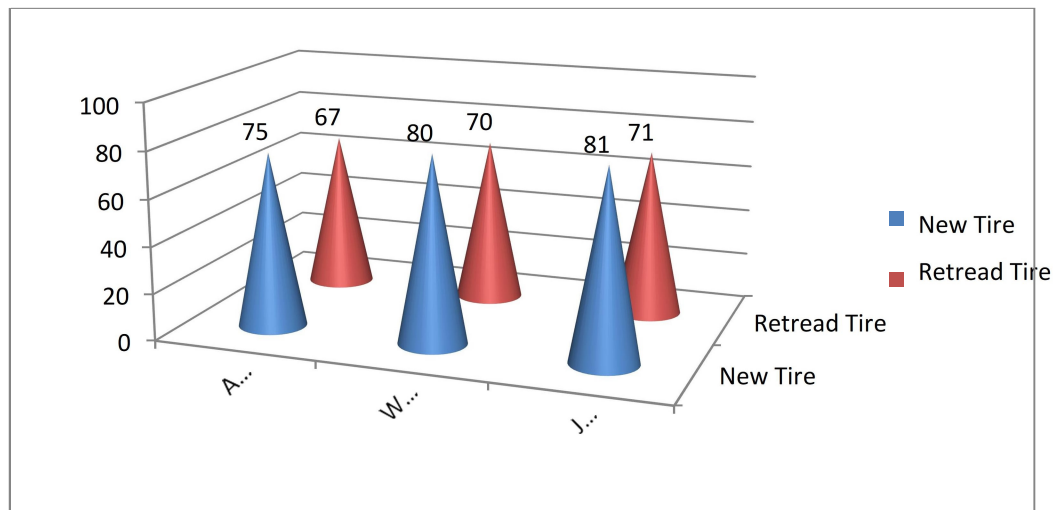


Figure 4.26: Mileage prediction by project

The temperature of the rubber in the tires' tread surfaces has a significant impact on how the tires behave (Berng, 2011). Tire adhesion, ride comfort, wear, and rolling resistance are all impacted by temperature. Additionally, there is a direct correlation between tire temperature and tire wear rate. The temperature is a major factor in the effects mentioned above.



Figure 4.27: Measuring Tread depth

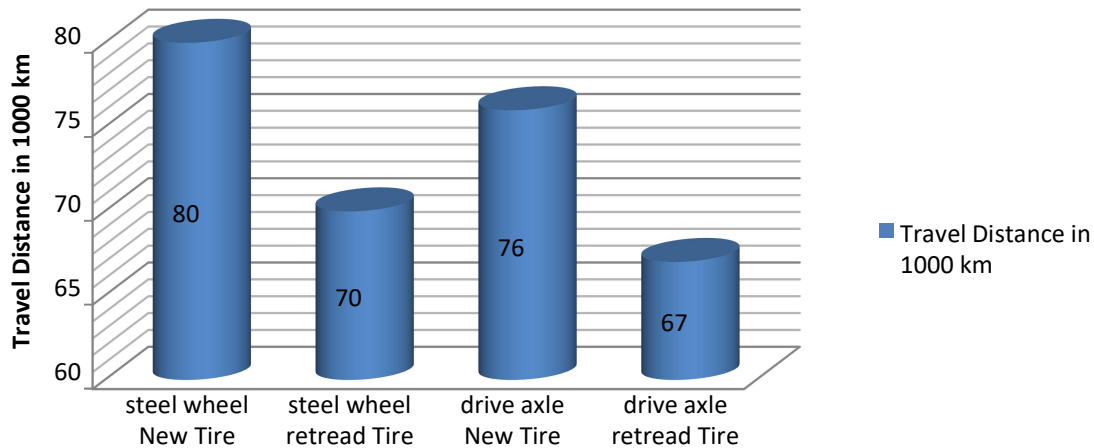


Figure 4.28: Mileage prediction by wheel position

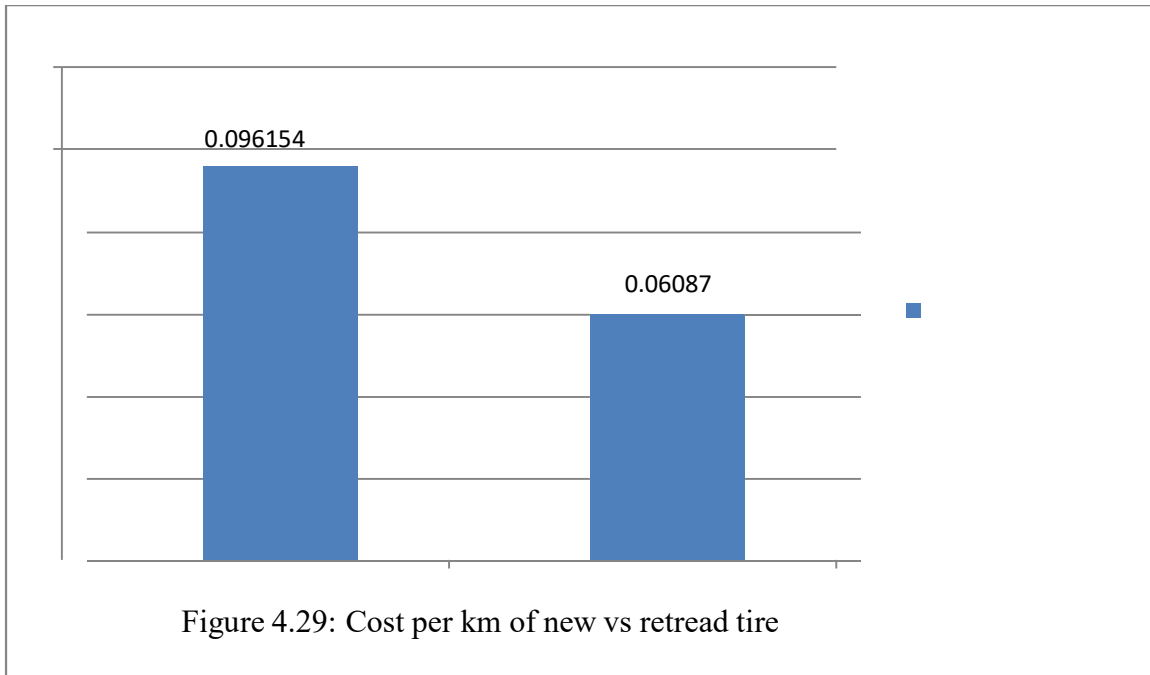
III. Comparative Study of Cost

Figure 4.29 shows a cost per km comparison between new and retread tire. The current price of new TRIANGLE 7.50R15LT tire is between 7000 to 8000 birr and for this study we took the average 7500 birr for cost comparison purpose. And according to ECWC data, the current price of retread tire of the same size is 3200 birr but this price doesn't consider the value of the casing since the corporation uses its own worn tire for retreading and the retread tires are used for the available fleet not for external customer. However the average current price of retread tire of the same size from the market is 4200 birr. Therefore we took this price for comparison purpose because it is more reliable and makes the study more valid.

When mileage is excluded, this seems like a significant savings. If we assume an average life of 100,000 kilometers for both new and retread tires, purchasing retread tires instead of new ones could result in savings of about 3300 birr, or 44%. However, the wear rate study and the total mileage prediction above indicated that average 13 % less mileage using retreads. By dividing the projected average total mileage of both tires to their respective price, we can get the cost of retread and new tire per km of travel which is:

$$\text{Cost per Km} = \text{Original Total Tire Cost} / \text{Total Km Travelled}$$

By taking mileage in to consideration, the cost of retread tire is 0.06087 birr per Km while that of new tire is 0.096154 birr per Km which is 37 % lower than new tire cost.



Some methodological issues arise when comparing the cost of a new tire and a retreaded tire. In the strict sense of the word, a retreaded tire is not the same as a brand-new tire. This is due to the fact that a retreaded tire cannot, in theory, simultaneously achieve the same level of qualities as the base product, a new tire, in terms of things like handling, durability, safety, and service life.

4.3 Result of Retread Tires' Defect Analysis

The purpose of this study is to identify the types of retread tire defects and their various causes so that appropriate actions can be employed by the managers of the corporation to improve the quality of retread tires.

The most common defects in retread tires include failure of tread, failure of the sidewall, failure of the buffer layer, bead delamination, penetration damage, sidewall cut, exposed ply, and bulges. In this study, a Pareto chart is used to organize the retread tire defects and to help the corporation in determining the severity of defects and identifying the appropriate solution to overcome the defects. The Pareto chart depicting various defects and their severity is presented in Figure 4.30. The Pareto chart shows the percentage frequency of various defects which are arranged in descending order. The steps involved in drawing the Pareto chart are as

follows. First, the common defects in retreaded tires have been identified through six months data of the corporation. The identified defects are further arranged in a sequence based on their severity level. Following this, using MS-Excel, the data has been plotted in the form of a bar chart showing the percentage-wise rating of defects and their cumulative percentage. It can be observed from the Pareto chart that the most severe defect of retread tire is the tread separation which is found about 38% of total defect generations in the retreaded tire. The other important defects include irregular wear, early excessive wear, failure of the side wall, bulge, casing defects, and bead delamination.

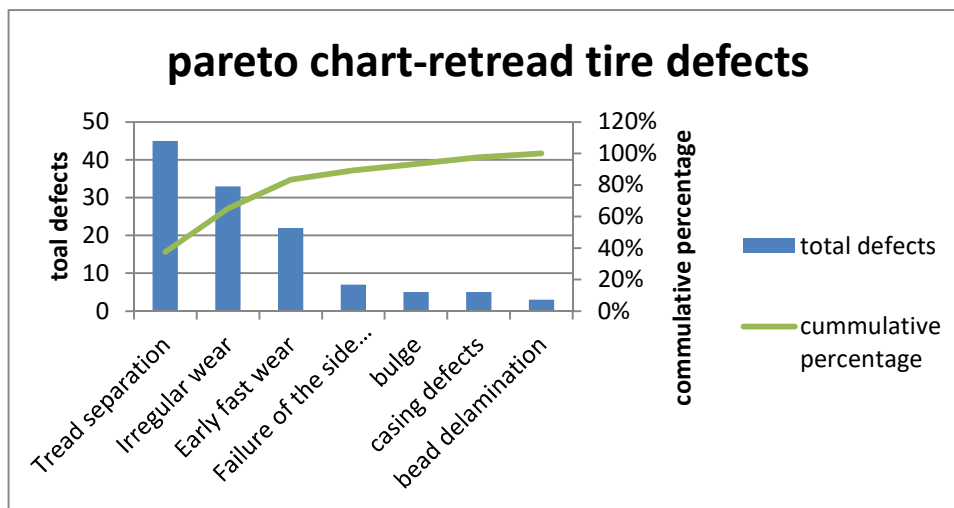


Figure 4.30: defects of retread tire in ECWC

The Table 4.5 illustrates the various causes of these defects which could be beneficial for managers in deciding how to control the occurrence of these defects. One of the major challenges is casing preparation, which requires skilled workers having the ability to pinpoint the problems in the casing. As there is no automated system to check the casing defects, it is done manually. Based on their skills and experience, the workers decide whether to accept the casings and proceed with the steps of tire retreading process. After the casing preparation, another challenge is to apply the pre-cure tread on the casing due to difficulty in finalizing the pre-cure tread length. To avoid the issue, the operator should measure the casing perimeter as well as tread length while assembling the tread in the tire casing.

Table 4.5: categories of defects and their possible causes

Category	Possible Causes	Valid and invalid tire retreading challenges	Source
Tread separation	• poor retread craftsmanship • poor quality of material specially tread rubber • improper cure conditions scorched • contaminated surfaces buffed	• lack of systematic work plan and process knowledge • lack of equipment for testing material composition and properties • lack of calibration of gauges, machines and instruments • contaminated storage area • Lack of awareness regarding tire retreading defects	(Woodrooffe et al., 2008), (Rosen Ivanov, 2016)
Irregular wear	• Lower tire curing rate • belt edge separation	• lack of systematic work plan and process knowledge • lack of calibration of gauges, machines and instruments	
Early fast wear	• incorrect skiving	• skive filling during the retreading process • Old technology-based machines	
Failure of the side wall	• incorrect inspection of worn tire before retreading	• Lack of training regarding inspection and quality control	

Based on the above causes and root causes, a list of action plan is formulated to minimize the defects and to mitigate the process challenges which is presented in Table 4.6.

Depending on the case at hand, the causes are classified differently, but it is a widely recognized approach to assume six key components that can contribute to an inappropriate characteristic, response, or impact. These components are materials, machine, man, measurement, process, and environment.

Table 4.6: Suggested Actions to Reduce the Defects

Type	Suggested action plan
Man	• The workers should be trained for the retreading process. • Experienced workers should be assigned for product and process quality checks. • Fostering problem identification and joint problem-solving approach. • Use of concurrent engineering and value stream mapping to develop standard work plan. • The development of standard operating procedure for handling tire defects and their causes.
Machine	• Maintaining the proper standard pressure during the curing process. • Maintaining the standard temperature during the curing process. • Machine design mold patterns used the latest technology tread patterns design. • Using either technological advanced machines or developing and installing innovative attachments in old machines. • Using calibrated measuring instruments to enhance the accuracy of process parameters. • Calculation of optimum curing time in the mold. • Developing periodic preventive maintenance plan.
Method	• Development of standard process specifications in tire retreading process. • Development of standard work procedure for hot and cold tire retreading. • Development of standard inspection methods. • Use of FIFO approach in tire retreading. • Use of standard material testing techniques to ensure the product quality.
Material	• Performing material composition testing. • Procuring raw material from certified suppliers • Implementing quality inspection for worn-out tires as well as tread to be

	applied.
Process	• Development of standard procedure for casing preparation and providing necessary training to workers. • Development of standard operating procedure for loading and unloading of tires • Selection of best procedure to make a perfect tread joint to avoid tread failure. • Development of standard operating procedure for the selection of specific tread pattern for specific tire size for better performance. • Selection of optimum treads depth for a particular application and providing TWI (tread wear indicator) to all remanufactured tires.
Environment	• Minimizing the energy consumption per kg of tires. • Minimizing the waste generation during tire retreading operations. • Development of guidelines for recycling and reuse of the waste generated during the process. • Investigating the effects of weather conditions (hot, cold, and humid) on the tire retreading process and developing the control parameters.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Following the completion of FEA study, the following conclusions were made:

- Static FEA is advised for use in tire design as it provided a good analytical evaluation and approximation of the mechanical properties studied in tires.
- The analysis process begins with the creation of a 2D FE tire model, and is then followed by an analysis of inflation pressure based on the 2D model. The 2D axisymmetric tire model was then rotated to create the 3D tire model. The 3D tire model was used to predict the shapes of inflated tires, tire static stiffness, and tire footprints under various operating conditions. Physical tests were used to confirm the predictions, and the results were satisfactory.
- Under operating conditions, it was discovered that for both types of tires, a higher vertical load results in a higher equivalent stress, total deformation, and ground contact area. On the other hand, although the equivalent stress was higher on both types of tires, the higher inflation pressure results in less overall deformation and ground contact area.
- As we can see from the simulation results, the equivalent stress, total deformation, contact area, and ground pressure distribution of the new tire and the retread tire are quite comparable, but the simulation result of the retread tire is a little bit higher than the new tire. These differences could be the result of various factors. Below is a list of them:

i. Inaccurate material characterization

Although this technique gives a reasonable estimate of the actual values, it may not produce very accurate results. As was mentioned in the previous chapter, the material property of retread tire was taken from the results published by (Balaramakrishna et. Al., 2009), in which hardness tests were used to characterize the elastic properties of the rubber compounds of retread tire. The sidewall stiffness, which in turn significantly affects the mechanical

characteristics of the tire, is greatly influenced by the characteristics of the apex (chaffer), sidewall, and beads. The elastic characteristics of the cords used in the new tire may be very different from those of the belts, nylon cap plies, and carcass plies. Due to the relaxation of the loads on the belt cords around the center of the contact region, these variations may lead to different pneumatic pre-stressed states, which ultimately have different effects (Pottinger, 2005).

ii. Inaccurate geometric representation

Additionally, the deflection of retreaded tires in response to vertical load varied between simulation and physical testing. This could be as a result of the tire's geometric details not being accurately represented. Small variations in profile geometries could have a significant impact on the mechanical characteristics of the tire. Even though great care has been taken to accurately represent the geometry, it may not be a very accurate representation of the actual tire.

Following the completion of this experimental study, the following conclusions were made:

- A reputable and well-managed method for creating premium remanufactured tires is retreading. Retreaded tires must pass a rigorous quality certification process that complies with the latest tire laws.
- According to the test results, retreaded tires have a shorter overall travel distance than new tires, but they also cost less per kilometer. Nonetheless, the total mile age is significantly higher than that of a new tire because retreading can be done on the same tire at least three times.
- Retread tire costs can be up to 44% less than those of new tires. Additionally, retreaded tires last 87% longer and cost 44% less than new tires.

After defect evaluation of retread tires, the following conclusions were made

The most important reasons for the defects is the lack of standard process guidelines regarding tire remanufacturing which have led the corporation to use unstandardized work procedures. These procedures are mostly faulty as the firm does not have the required skilled personnel as well as advanced technologies

The present work highlights the most prominent defects and the reasons for their occurrences have been identified and a comprehensive list of action has been provided which could provide necessary insights to the managers while developing a roadmap for the development of high quality and high-performance retread tires. The use of quality tool like the Pareto chart has provided a clear picture of the current situations as well as the actions that can be taken to improve them. Hopefully, the present work would prove beneficial for the firm to adopt and excel in the tire remanufacturing.

5.2 Recommendations

This study is an initial attempt at testing and simulating a comparison between new and retread tires to see how well the former performs in relation to the latter.

This paper's static tire FEA results demonstrate that this method can be effectively applied to tire design in order to forecast or enhance tire characteristics. In order to fine-tune the desired tire behavior to existing theories and experience, Finite Element Analysis (FEA) expedites the tire design process and allows the designer to explore a multitude of designs quickly. However, it aids in the early detection of potential influences that would otherwise be unpredictable on tire mechanical behavior and durability.

A structural static FEA provides a good price-performance for use in tire design, though dynamical and thermal behavior, as well as time-dependent material properties like viscoelasticity, should not be overlooked when the tire service is taken into account. I advise future research to surpass and add on additional improvement since the analysis of steady staterolling tires, in addition to static FEA tire analysis, will yield very concrete results.

A reputable and well-managed method for creating premium remanufactured tires is retreading. Retreaded tires must pass a rigorous quality certification process that complies with the latest tire laws. Retreaded tires can have a lower failure rate and often have an equivalent lifespan to new tires because tire casings are extensively inspected and tested, and pre-cured tread or mold-cure rubber compound is selected with the intended use in mind.

From a safety perspective, the retreaded tire is not used for expensive and precise item transportation.

Too many truck fleet operators, according to (Deierlein, 1996), did not remove the tires for retreading until the tread depth had worn down past the point of safety. This practice has a detrimental effect on the casing's suitability for retreading, or its durability for numerous retreads. It may be carried out as a cost-saving measure or to postpone a purchase. This is due to the requirement that the casing have a minimum amount of tread in order to lower the risk of steel belt damage.

The mold cure procedure, which was formerly the recommended approach, was not very effective. In actuality, retreads separate from casings as a result of mold curing. Precuring is the preferred approach these days because of this. The new procedure is credited for improving retread safety on its own. Furthermore, there are stricter inspection requirements for casing before the process starts. It all seems reasonable. A poor foundation cannot be provided by old or damaged casings. For this reason, many fleets have a maximum number of retreaded casings.

The relevant database for this decision-making problem must be provided, and a statistical analysis of all tires must be completed in order to reach a final decision regarding retreading. In addition, the data for every subsystem (facility) must be homogenized with regard to the kind of vehicle and the circumstances surrounding its use. That is the only way a big transportation company that has chosen to use retread tires can determine if and when using retread as a modern industrial and logistical process is a financially advantageous course of action.

The study is useful for businesses that offer retreading services. In that instance, though, each tire received for retreading would require a precise and trustworthy "history" of its exploitation. If retreading is done on a tire whose user is unknown, that is challenging to accomplish in practice.

5.3 Future work

i. FE Tire Model Future Work

It is possible to increase accuracy even further. An enhanced outcome would be obtained with a more precise distribution of contact pressure in both the longitudinal and lateral directions. This paper assumes a cylindrical tire with uniformly distributed contact pressure in the lateral

direction. In actuality, the sidewall region experiences higher pressure than the contact's deeper interior. Aspect ratio and tread pattern also affect distribution. To improve accuracy, road roughness should also be taken into account when calculating contact.

The research is conducted solely using linear materials. When examining the models' pressure values and equivalent stresses, this should be taken into account. Further research is necessary, but the materials used in actual pneumatic tires exhibit more non-linear behavior.

ii. Experiment Future Work

Future research will involve adding measurements for a faster slip angle sweep rate, akin to the BV12 and flat belt measurements, to the existing vehicle-based measurement set. In order to compare the tire surface temperatures for various slip angle sweep rates, temperature should also be measured during these experiments. Additionally, a tire model will be fitted to the vehicle-based measurements as part of a full-vehicle validation. We will look into how various operating conditions affect the tire model that results, which in turn affects the behavior of the entire vehicle. As a result, future measurements ought to be carried out under real-world operating conditions that are comparable to both those used in the flat belt measurements for the tire model's validation and those used in the full-vehicle model's validation.

The temperature in the contact patch will vary depending on the operating conditions of each project. Therefore, more measurements where the temperature is directly measured and its impact on the wear rate is investigated should be made.

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APPENDICES

Appendix A – RP 203A Test Procedure



RP 230A

VMRS 017

TIRE TEST PROCEDURES FOR TREAD WEAR, SERVICEABILITY AND FUEL ECONOMY

PREFACE

The following Recommended Practice is subject to the Disclaimer at the front of TMC's *Recommended Maintenance Practices Manual*. Users are urged to read the Disclaimer before considering adoption of any portion of this Recommended Practice.

PURPOSE AND SCOPE

The purpose of this Recommended Practice (RP) is to provide fleets guidelines on tire testing procedures. The RP is organized in three parts:

- Tire Testing Procedures—Tread Wear
- Tire Testing Procedures—Serviceability
- Tire Testing Procedures—Fuel Economy

The Tread Wear section provides information to help fleets evaluate tires through one complete tread life cycle (either new or retreaded) from initial placement on a vehicle to removal at wear out or for any other reason.

The Serviceability section provides information to help fleets evaluate tires through a complete casing life cycle—from initial placement on a vehicle as a new tire through multiple retreads and ending when casings are disposed, sold or placed on sold or traded vehicles.

The Fuel Economy section is a supplement to TMC Recommended Practices RP 1102, *TMC/SAE In-Service Fuel Consumption Test Procedure—Type II*, and RP 1103, *TMC/SAE In-Service Fuel Consumption Test Procedure—Type III*. It provides specific information to help fleets evaluate the effects of tire variables (brands, types, etc.) on vehicle fuel consumption.

SECTION I

TREAD WEAR TIRE TEST PROCEDURES

The objective of this section is to help fleets reduce the number of variables that can influence test result quality. Procedures for calculating tire cost per mile are provided in the **Appendix**.

A tread wear test can be combined with a tire serviceability test. A recommended test procedure for serviceability appears in **Section II**.

TREADWEAR TERMINOLOGY

Tire treadwear can be analyzed in terms of wear rate, irregular wear, resistance-to-irregular wear, and/or removal mileage.

Wear rate is usually expressed in terms of miles-per-32nd inch of worn tread depth. Wear rate can be tracked during tire life and used to calculate projected tire removal mileage. Projected mileage should only be used as a tire performance indicator. Final analysis of performance should be made using actual removal mileage.

Irregular wear is defined as non-uniform wear of individual tread elements or elements around the tire. Some examples include heel/toe wear, diagonal wipes, high/low wear, etc. **NOTE:** See TMC RP 219B, *Radial Tire Wear Conditions and Causes*.

Removal mileage is the number of miles a tire has accumulated when removed. This is often the most important tire performance consideration. Take care to document reasons for removal (i.e., road hazards, irregular wear, pull point, etc.) and separate tire-related removal causes from other removal causes when analyzing data.

TIRE TEST EXAMPLES

Many factors affect tire treadwear. The following are examples of different treadwear tests that can be run. It is important to test only one variable at a time to ensure data quality and avoid confusion.

Examples

Tire brand (new tires):	Brand A 123 vs. Brand B 456
Tread type within brand:	Traction Tread vs. Rib-Type Drive Tires
Retread brand:	Brand C ABC vs. Brand C DEF

Retread process:	Pre-cure vs. Mold Cure
Tire size:	Conventional vs. Low-Profile
Wheel or rim size:	22.5" vs. 19.5"
Inflation pressure:	Minimum Required for Load vs. Increased Pressure
Tire rotation procedure:	No Rotation vs. Left-Right
Vehicle Type:	COE vs. Conv. or Std. vs. Set-back Axle
Vehicle Brand:	Brand AB vs. Brand CD
Alignment:	Positive vs. Negative Camber or Toe Setting

TREAD WEAR TEST CONSIDERATIONS

A. Number Of Tires Required

For steer, drive and trailer tire tests, TMC recommends that fleets have a sample of 30 tires for each individual test type or test group at the **end** of each test. This allows fleets to obtain statistically significant and repeatable data. Smaller sample sizes may provide useful data that indicate differences between tire groups in the test, but the results may not be statistically significant or repeatable. Refer to "Test Group Sample Size Table" in the **Appendix** for an indication of the value of smaller sample sizes.

B. Vehicle Specification

Tire wear rate and wear uniformity can vary with vehicle type, make, year and major components. The fewer the variables, the better the data. To account for major vehicle effects, follow these guidelines during test setup:

- Use identical vehicles for all test groups unless vehicle type is the test variable.
- If vehicles of different specification must be used, make sure they're equally represented in each test group.
- Make sure the test vehicles are representative of the fleet's equipment.
- Use new vehicles (highly recommended).

C. Gross Vehicle Weight

Make sure the load weights of all test vehicles are similar to ensure fair evaluation between test groups.

D. Wheels

Follow these guidelines:

- Make sure all wheels in the test are of the same width (unless different tire sizes require different width).
- Inspect all wheels for damage, excessive runout and wobble.

- Use new valve stems and grommets when tires are mounted.
- Be consistent regarding the use of aluminum and steel wheels on test vehicles.

E. Wheel Position

Tire wear rates, irregular wear, wear uniformity, and removal mileage also vary with axle and wheel position.

F. Steer Tire Wear Testing Variables

Wear rates for left-side and right-side steer axle tires are seldom equal. Reasons for different tire wear rates from right side to left side are normally combinations of the following:

- Road Crown
- Vehicle Steering Geometry
- Frequency and Angle of Left and Right Turns
- Total Vehicle Alignment

Typically, the right front tires on commercial trucks wear more slowly than do the left front tires on the same vehicle. However, right-side tires are more susceptible to irregular wear conditions that can cause early removal—despite acceptable remaining tread depth.

G. Drive and Trailer Tire Wear Testing Variables

On multiple axle configurations, wear rates will vary from axle to axle.

H. Tire Position Rotation

Due to the typical differences in treadwear for various wheel positions, fleets often rotate tires by position to even out wear. For testing purposes, this procedure should only be used if it is normal fleet policy. If position rotation is desired, tires must be rotated in the same manner and at the same test mileage interval on all vehicles in the test.

I. Total Vehicle Alignment

Axle alignment is a particularly critical variable. Follow these guidelines:

- Align all vehicles at the start of the test.
- Align steer and drive axles to fleet specifications. See TMC RP 642A, *Guidelines for Total Vehicle Alignment*.
- Check vehicle alignment if unusual wear develops during the test.
- Keep all alignment records.

J. Vehicle Maintenance

Make every effort to replace worn steering system and suspension system components that are likely to

need replacement before testing begins, then align the vehicle. Minimize any changes to test vehicles during the test.

K. Tire Maintenance

During the test, remove any nails (that do not cause air leakage) found embedded in the tread of any tires.

Tires with objects that have penetrated the casings should be repaired and returned to their test position with the same direction of rotation if possible. If this is not possible, the damaged tire is considered "lost." For proper repair procedures, refer to TMC RP 206A, *Tire Repair Procedures*.

L. Tires Removed Before Test Completion

Tires damaged beyond repair must be dropped from the test. If the damaged tire is mated with another tire of a dual assembly, the mate must also be dropped from the test as differences in tire diameter will affect the test outcome. Note the specific reason for tire removal, tread depth and the accumulated mileage. Separate removal causes into two categories: tread wear related and non-tread wear related (such as vandalism or vehicle accident). Do not discard data collected on the removed tire or tires as it may be beneficial during data analysis.

M. Air Pressure

Follow these guidelines:

- Follow fleet practices (unless air pressure is the test variable).
- Be sure that inflation pressure is adequate to carry vehicle load.
- Check/correct cold inflation pressures at least monthly (preferably weekly) with a calibrated gauge.
- Keep records showing "pre-correction" inflation pressures.
- Use positive seal metal valve caps.

N. Weather

Follow these guidelines:

- Install all test tire groups within 30 days.
- Make every effort to ensure that the vehicle routes for each test group experience the same weather. If the test vehicles are exposed to large variations in weather, make every effort to ensure that each test group is equally exposed to these variations.

O. Geography

Follow these guidelines:

- Make sure truck routes for each test group

share the same geographic area.

- Make sure route geography is representative of fleet operation.
- Use a domiciled fleet if possible. Experience has shown using a domiciled fleet (or portion of a fleet) reduces geographic variations.

P. Drivers

Follow these guidelines:

- Screen out drivers with known unusual driving habits.
- Make sure drivers are representative of fleet personnel.

Q. Casing Manufacturer

When testing retreaded tires, be sure comparisons are made with casings made by the same manufacturer (if casings are not the test variable). A retread wear test with "mixed" casings, mixed tread designs or tread widths may invalidate test results.

R. Tire Age

All new tires and retreaded casings in a tread wear test must be manufactured within one year of each other as designated by the last three or four digits of the DOT number on each tire sidewall. See TMC RP 218C, *DOT Tire Identification Codes* for information on reading DOT tire codes.

UNIQUE TIRE IDENTIFICATION

It is very difficult to document tire wear data confidently without unique identification of individual tires, since tires are often removed from service or moved to another wheel position or vehicle without formal documentation. Unique tire identification may not help locate a lost tire, but it will indicate if tires have been lost or moved from their intended positions as data is collected throughout the test duration.

Labeling all test wheels and vehicles with a visual identification mark may help alert maintenance personnel and drivers that the wheels and vehicles are part of a test.

STATISTICAL METHODOLOGY FOR TIRE TREAD WEAR TESTING

At least two products must run concurrently during testing. All parameters for the test and control vehicles, except for the test variable, must be consistent. See **Fig. 1** for tread wear evaluation positions.

For tire mileage testing, measure remaining tread depth at specific intervals. The recommended mileage intervals in line-haul operations for all wheel

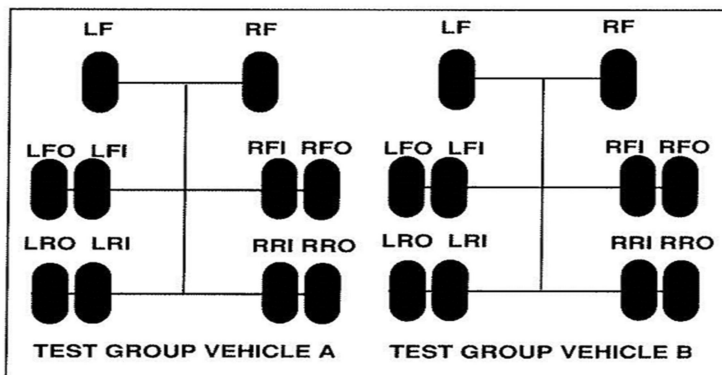


Fig. 1: Positions for Tread Wear Evaluation

positions are at least every 30,000 miles or at scheduled preventive maintenance intervals. Measurements are not significant prior to 30,000 miles since most tires wear more quickly in their early tread life than their remaining tread life.

Tire mileage projections should not be based on early tire mileage wear, but projections can be made when at least 50 percent tread wear has occurred. Such projections should be used only as indicators of tire performance.

For high wear conditions such as pick-up and delivery, construction, mining and refuse operations, use percentages of "expected removal"—such as 25 percent, 50 percent, 75 percent—and "at removal" as measuring intervals. The percentages may be based on mileage or time, depending on the fleet's normal means for determining tire life.

For smaller test samples, tire test groups can be mixed on the same vehicle to equalize exposure to random variables. The following are test tire installation methods for single and tandem axles.

Single Axles

For single axles with dual tire assemblies, a left-side, right side installation method can be used for test groups, as shown in Fig. 2.

Tandem Axles

The X-pattern method for tandem axle vehicles is shown in Fig. 3.

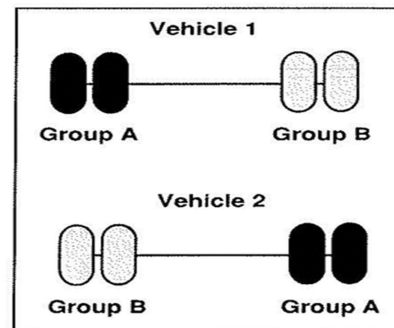


Fig. 2: Right-side, Left-side Installation Method

NOTE: Mixing sample groups on vehicles is less important as sample size increases.

TIRE LOSSES

During the course of the test, it is expected that several tires will be unserviceable due to road hazards or other conditions. When a tire fails, note the cause and the mileage at the time of failure. When one tire of a dual assembly fails, drop the companion tire from the test.

TEST DATA COLLECTION AND RECORDING

The simplest means of recording test data is by using paper forms. (See **Appendix** for sample tire installation and inspection data forms.) Hand-held computers can also be used to gather tire performance data.

Tire tread condition must be noted and a tread condition coding system makes recording, filing and

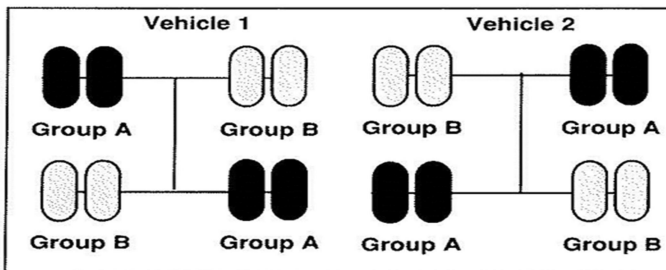


Fig. 3: X-Pattern Installation Method for Tandem Axles

analyzing test data easier. See the **Appendix** for a complete list of codes with suggested abbreviations.

NOTE: Refer to TMC RP 219B, *Radial Tire Conditions Analysis Guide* for detailed photographs and descriptions of all tire conditions/failures.

RECOMMENDED TOOLS FOR TEST

The following tools are recommended for tire treadwear testing:

- Air gauge
- Tread depth or “non-skid” gauge
- Pliers
- Awl/Probe
- Small mirror (to aid reading brand numbers between duels)
- Tire crayon or chalk
- Flashlight
- Clipboard
- Appropriate forms
- Digital camera

TIRE TREADWEAR MEASUREMENT

Tread depth measurements are typically taken with a simple tread depth or “non-skid” gauge. Units of measurement are typically 32nds of an inch or millimeters. Electronic depth gauges with digital readout are also available and are acceptable for treadwear measurements. However, periodic calibration of the gauge is critical.

The minimum number of tread depth measurements needed is one measurement per “major groove” in two “representative” locations about 180° apart. Be sure to take tread depth measurements at the lowest part of a major tread groove. The valve stem can be used as a reference to ensure tread depth measurements are taken at the same locations.

TIRE INSPECTION PROCEDURE

Follow these guidelines:

- Tires must be available for periodic inspection at predefined intervals.
- Only one person should take measurements (for data consistency).
- Measure or check the following items:
 1. Inflation pressure.
 2. Tread depth measurement as described previously.
 3. Treadwear uniformity (irregular wear).

4. Sidewall appearance (cuts, snags, etc.).
5. Other evaluation points (stone holding, for example).

- Note driver comments on tire performance (such as ride and wet traction).

DATA ANALYSIS

Although it is best to complete a test before drawing any conclusions, indications of tire performance may be made when tires are at least 50 percent worn. Use the same analysis procedures for preliminary analysis (detailed in the following paragraphs) but, remember, the data must be interpreted as projections *not* as a final test result based on removal mileage. Data acquisition for all test and control tires should end at the same mileage or a wear rate should be used for wear out.

When the test is complete and data has been gathered, final analysis of results can begin. The test variable can be evaluated for wear rate, irregular wear and removal mileage.

1. For Steer Tires:

List removal mileages for all tires that complete the test. Exclude tires that are removed for non-wear related reasons (vehicle accidents, vandalism, etc.) Include tires that were removed due to manufacturing defects. Compute the average (Avg.) left steer tire mileage for each test group by adding the total removal mileage of all left steer tires and dividing by the number of tires that completed the test from that group.

Group A (Steer Axle Tires)

$$\text{Average Steer Mileage (Avg. Steer)} = \frac{\text{Total Miles Traveled by Steer Tires (A)}}{\text{Total Number of Steer Tires (A)}}$$

Repeat this procedure for each test group of tires.

2. For Drive And Trailer Tires:

List removal mileages for all tires that complete the test. Exclude tires (and the corresponding dual mate tire) if they are removed for non-wear related reasons. Include tires that were removed due to manufacturing defects.

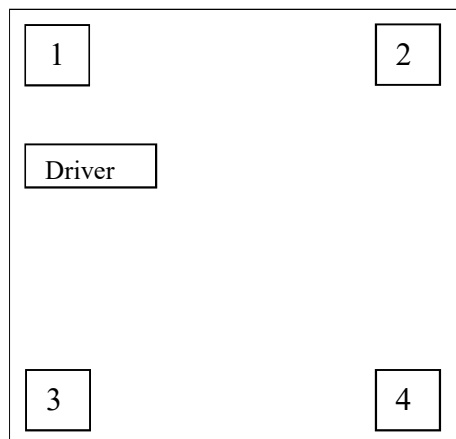
Average the removal mileage for all drive or trailer wheel positions. See **Fig. 4** for positions.

Appendix B – Specific Test Procedure

Tire Test Procedures

1. Install test tires in assigned positions on test vehicles;
2. Mount tires using new valve stems with metal valve caps;
3. Measure tread depths at valve stem & 180 degree offset as specified;
4. Install test tires decals on vehicle above pairs;
5. All measurements will be taken every 5000 miles at scheduled service intervals;
6. Pre-correction cold air pressures will be noted for all study tires;
7. Air pressures will thereafter be corrected to 100 psi throughout the length of test; Note wear uniformity, sidewall appearance, and repairs (where applicable);
8. Take pictures with date stamp of all tires removed because of non-wear reasons;
9. Submit all pictures and data sheets (via email or Fax 252-830-3149) to Buddy Dixon as they are taken/prepared; and
10. Buddy Dixon will compile all information and send to the NCAT Pavement Test Track.

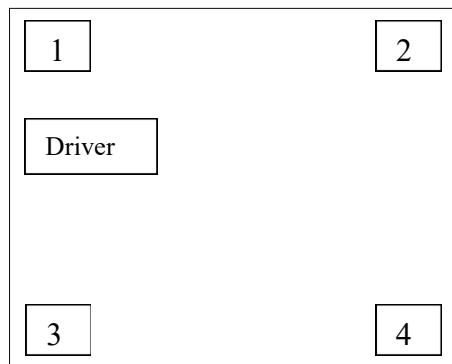
Tire Positions



Appendix C –Tire Study Data Collection Forms

1. Use the attached mileage evaluation form to document all required data when evaluating tires
2. This form is used for mileage comparison between retread and new tire
3. Each tire is branded with specific identification number for tracing purpose
4. Two retread tires will be installed in one side in position 1 and 4 while the new tires will be installed on the opposite side in position 2 and 3
5. Tread depth measurements should be taken on each tire rotation
6. When rotating tires, all tires will move to the opposite side of the vehicle from the outside position to the inside or inside to outside.
7. In addition to normal rotation and tread depth measurement, all other tire maintenance activities should be recorded
8. If a tire needs replacement before the end of the test, it must be replaced with identical tire

Tire position



Stem



Evaluation form

Equipment Number

Tire size

Vehicle location

Contact

Test to be evaluated

Initial Installation data

Vehicle Mileage

Date

Tread Depth

Tire Position	Tire Type	Stem	Offset	Remark
1				
				
				
				
				
2				
				
				
				
				
3				
				
				
				
				
4				
				
				
				
				