Universidade Federal
do Rio de Janeiro
Escola Politécnica

APPLYING TIRE MODELS TO MICHELIN TIRES FOR WEAR ESTIMATION

Gabriel de Carvalho Ferreira Silva

Projeto de Graduação apresentado ao Curso de Engenharia Mecânica da Escola Politécnica, Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Engenheiro Mecânico.

Orientadores: Fernando A. N. Castro Pinto
Marcio de Almeida D'Agosto

Rio de Janeiro
Setembro de 2019

UNIVERSIDADE FEDERAL DO RIO DE JANEIRO

Departamento de Engenharia Mecânica

DEM/POLI/UFRJ

APPLYING TIRE MODELS TO MICHELIN TIRES FOR WEAR ESTIMATION

Gabriel de Carvalho Ferreira Silva

PROJETO FINAL SUBMETIDO AO CORPO DOCENTE DO DEPARTAMENTO DE ENGENHARIA MECÂNICA DA ESCOLA POLITÉCNICA DA UNIVERSIDADE FEDERAL DO RIO DE JANEIRO COMO PARTE DOS REQUISITOS NECESSÁRIOS PARA A OBTENÇÃO DO GRAU DE ENGENHEIRO MECÂNICO.

Aprovado por:

____
Prof.º Fernando Augusto de Noronha Castro Pinto, Dr.Ing.

____
Prof.º Marcio de Almeida D'Agosto, D.Sc.

____
Prof.º Gabriel Lisbôa Verissimo, D.Sc.

____
Prof.º Silvio Carlos Anibal de Almeida, D.Sc.

RIO DE JANEIRO, RJ - BRASIL

SETEMBRO DE 2019

De Carvalho Ferreira Silva, Gabriel

Applying tire models to Michelin tires for wear estimation/Gabriel de Carvalho Ferreira Silva. – Rio de Janeiro: UFRJ/Escola Politécnica, 2019.

XII, 30 p.: il.; 29,7cm.

Orientadores: Fernando Augusto de Noronha Castro Pinto

Marcio de Almeida D’Agosto

Projeto de Graduação – UFRJ / Escola Politécnica / Curso de Engenharia Mecânica, 2019.

Bibliography: p. 31.

1.Tire. 2.Wear. 3.Finite Elements Method. 4.Numerical Simulation. 5.Michelin. 6.LAVI. 7.LTC. I.Fernando Augusto de Noronha Castro Pinto. II.Marcio de Almeida D’Agosto. III.Universidade Federal do Rio de Janeiro, Escola Politécnica, Curso de Engenharia Mecânica. IV.Applying tire models to Michelin tires for wear estimation

Resumo do Projeto de Graduação apresentado à Escola Politécnica / UFRJ como parte dos requisitos necessários para a obtenção do grau de Engenheiro Mecânico.

APLICAÇÃO DE MODELOS PNEU EM PNEUS MICHELIN PARA ESTIMAÇÃO DE DESGASTE

Gabriel de Carvalho Ferreira Silva

Setembro/2019

Orientadores: Fernando Augusto de Noronha Castro Pinto
Marcio de Almeida D'Agosto

Curso: Engenharia Mecânica

O uso de modelos para a predição do desgaste é de suma importância para a indústria de pneus. Estes modelos, teóricos e/ou empíricos, aliados a dados de telemetria de veículos e ao método de Elementos Finitos, auxiliam os desenvolvedores de pneus na melhoria contínua do produto em termos de desempenho. Nesse contexto, o estudo de métodos capazes de unir essas ferramentas é desejado a fim de criar formas preditivas do comportamento do pneu durante o uso. Este trabalho tem como objetivo principal estudar o comportamento de modelos teóricos de desgaste, aliá-los ao método de Elementos Finitos e criar uma metodologia de estimação do desgaste em relativo, em uma colaboração entre o Laboratório de Acústica e Vibrações (LAVI) da COPPE, o Laboratório de Transporte de Carga (LTC) da COPPE e a Michelin. Para isso, o programa MATLAB e o software de Elementos Finitos desenvolvido pela Michelin são utilizados.

Palavras-chave: pneu, desgaste, método de elementos finitos, simulação numérica, Michelin, LAVI, LTC

Abstract of Undergraduate Project presented to POLI/UFRJ as a partial fulfillment of the requirements for the degree of Engineer.

APPLYING TIRE MODELS TO MICHELIN TIRES FOR WEAR ESTIMATION

Gabriel de Carvalho Ferreira Silva

September/2019

Advisors: Fernando Augusto de Noronha Castro Pinto
Marcio de Almeida D'Agosto

Course: Mechanical Engineering

The application of tire models for wear prediction is of the utmost importance for the tire manufacture industry. These models allied to telemetry data and the Finite Element method assist tire developers in the tire's continuous improvement in terms of performance. In this context, the study of methods that are able to combine these tools is desirable to predict the tire's behavior during its use. This work aims to study the models behavior, ally them to the Finite Element method and create a methodology to estimate tire wear in relative, in cooperation between the Acoustics and Vibrations Laboratory (LAVI) COPPE, the Cargo Transport Laboratory (LTC) COPPE and Michelin. To do so, it is used MATLAB and the Finite Element software developed by Michelin.

Keywords: tire, wear, finite element method, numerical simulation, Michelin, LAVI, LTC

ACKNOWLEDGEMENT

Agradeço à minha família por todo o apoio ao longo da faculdade, em especial, aos meus pais, Raquel e Roberto, por sempre estarem presentes e dispostos a me apoiar. Sinto-me um privilegiado de tê-los como pais. Também ao meu primo-irmão, Davi, pelas revisões e sugestões feitas ao texto.

Agradeço também à minha companheira e amiga, Camila, por todo o apoio e parceria durante a faculdade na França e no Brasil, tornando o dia a dia mais leve.

Agradeço à equipe do setor de Pesquisa e Desenvolvimento da Michelin em Campo Grande por me permitirem trabalhar neste tema em parceria com a UFRJ, sempre mostrando interesse no desenvolvimento do projeto, e pelos bons momentos passados na empresa. Em especial a Mario Nakayama por ter sido tutor e amigo ao longo desses quase dois anos de estágio, a Eric Lebreton pela orientação constante, a Flavia Fernandes pela sugestão do tema e acompanhamento, a Celso Oliveira pelo interesse e acompanhamento do projeto, a Pedro Tersiguel por sempre estar disposto a ajudar, a Livia Tovar pelo interesse e entusiasmo, a Julio Batista pela ajuda com a divulgação do questionário e a Julia Coelho Santos pela parceria neste projeto junto à Michelin.

Agradeço também aos meus orientadores, professor Fernando Castro Pinto e Marcio D’Agosto por estarem desde o início dispostos a me guiar e aconselhar ao longo do desdobramento do projeto.

Agradeço ao professor José Luis da Silveira e Tobias Beilicke pela orientação e acompanhamento durante o meu duplo diploma na SIGMA Clermont.

Agradeço à CAPES pela bolsa que me proporcionou durante meu duplo diploma na França e ao CNPq pela bolsa de Iniciação Científica na UFRJ. Espero que cada vez mais alunos tenham as oportunidades que me foram concedidas.

Por fim, agradeço aos professores, integrantes e ex-integrantes do Laboratório de Máquinas Térmicas da UFRJ, LMT, pelos três anos de estágio técnico e Iniciação Científica durante o meu percurso na UFRJ. Em especial, ao engenheiro Nauberto Rodrigues Pinto pelos incontáveis conselhos e pela amizade que continuam até hoje.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Motivation

The tire is an essential component of the mobility industry as the only connection of vehicles to the road. It is responsible for adherence, comfort, rolling resistance, among other performances. A misconceived tire has the potential to damage a vehicle performance and, in the worst case scenario, endanger its user.

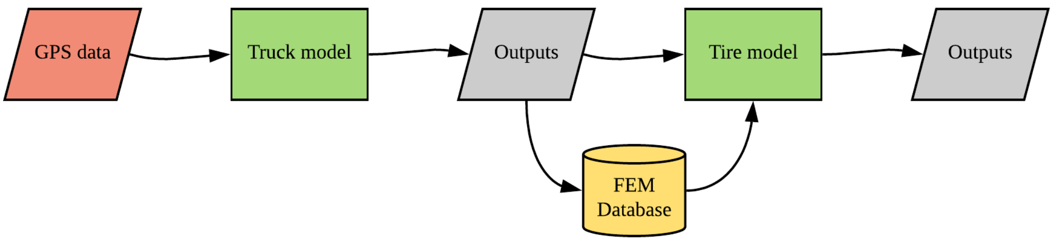
In the process of developing tire conceptions, tests and simulations are made in order to anticipate the product's behavior. These studies predict the tire wear, the temperatures that tires will be submitted to, the adherence behavior, the rolling resistance, as well as other performances estimates for different client conditions.

Therefore, research in terms of estimation methods to comprehend tire wear is quintessential for simulations to be in agreement with reality. The final objective is to give a more precise result and add data to the tire's conception.

1.2 Subject's presentation

To define test and simulation parameters that contribute to the conception of a new tire, GPS data is collected and analyzed so as to comprehend the usage conditions of the tire. This data is often used in a vehicle model capable of translating accelerations to charges submitted to the tire in the three directions.

Figure 1 – Project's schema



The truck model at Figure 1 was developed by Julia Coelho Santos during her R&D Internship for Michelin in Campo Grande, while the tire model and the Finite Element Method (FEM) database were developed by Gabriel de Carvalho Ferreira Silva, R&D Intern at Michelin Campo Grande.

This project was conducted at Michelin under the supervision of tire developers and the mentoring of two professors from the Polytechnic School of the Federal University of Rio de Janeiro (UFRJ). Therefore, this public report focuses on non-confidential aspects of the project, such as the model development and results.

1.3 Project's objective

The purpose of this work is to study and compare different tire models, to better understand the influence of models' parameters on tire wear and to create an algorithm on MATLAB which is able to compare different tires using different wear models and conditions, in particular, tire inflation. To do so, the project embraces a bibliographic research on tire's mechanical behavior and tire wear and a market research to comprehend carriers' usage in order to use this information on Finite Elements simulations.

The models used are Archard's model, Shallamach's model and Michelin's wear model. Michelin's model, for confidential reasons, will not be revealed, but the results will be presented for comparison nonetheless.

This work focus on truck tire modelling, but the methodology is applicable to any type of tire.

1.4 Report's objective

The present report covers the market research, the tire model development, the database created by Finite Elements simulations that feeds the tire model and the results obtained. The vehicle model developed by Julia Coelho Santos is referenced in the bibliography [1].

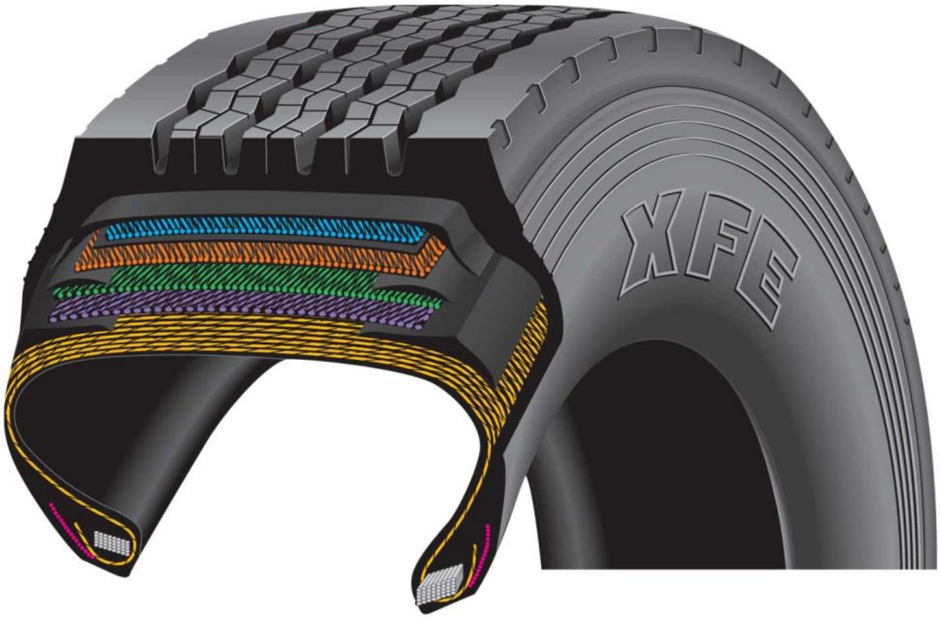
2 TIRE

2.1 Tire structure

As the only connection between the vehicle and the road, the tire is responsible to withstand the load and speed variations as well as road and weather conditions. Thus, tires today are made of several layers that are produced from different types of materials: natural and synthetic rubber, steel cables and, sometimes, a textile cover. The combinations of these different materials aligned with a defined geometry are responsible for the tire's performance in terms of adherence, rolling resistance, braking distance, lifespan, temperature, etc.

Each manufacturer has its own range of materials. However, the overall structure of a truck tire does not change much as it can be seen on Figure 2.

Figure 2 – Truck tire's overall structure [2]



A truck tire can be divided into two regions: the tread band and the carcass. The tread band has grooves that promote water flow, avoiding aquaplaning, and a specific geometry that is related to its use, whether it is meant for asphalt, sand, rock or mixed use.

The carcass has 4 metallic layers that protect the tire from road irregularities and keep the whole tread band in contact with the road in order to provide adherence. The radial metallic layer that surrounds the tire is responsible for the tire's rigidity. The tire's bead at the low zone region keeps the tire connected to the wheel and a smaller metallic layer is meant to protect the low region from being strangled by the tire rim and the wheel.

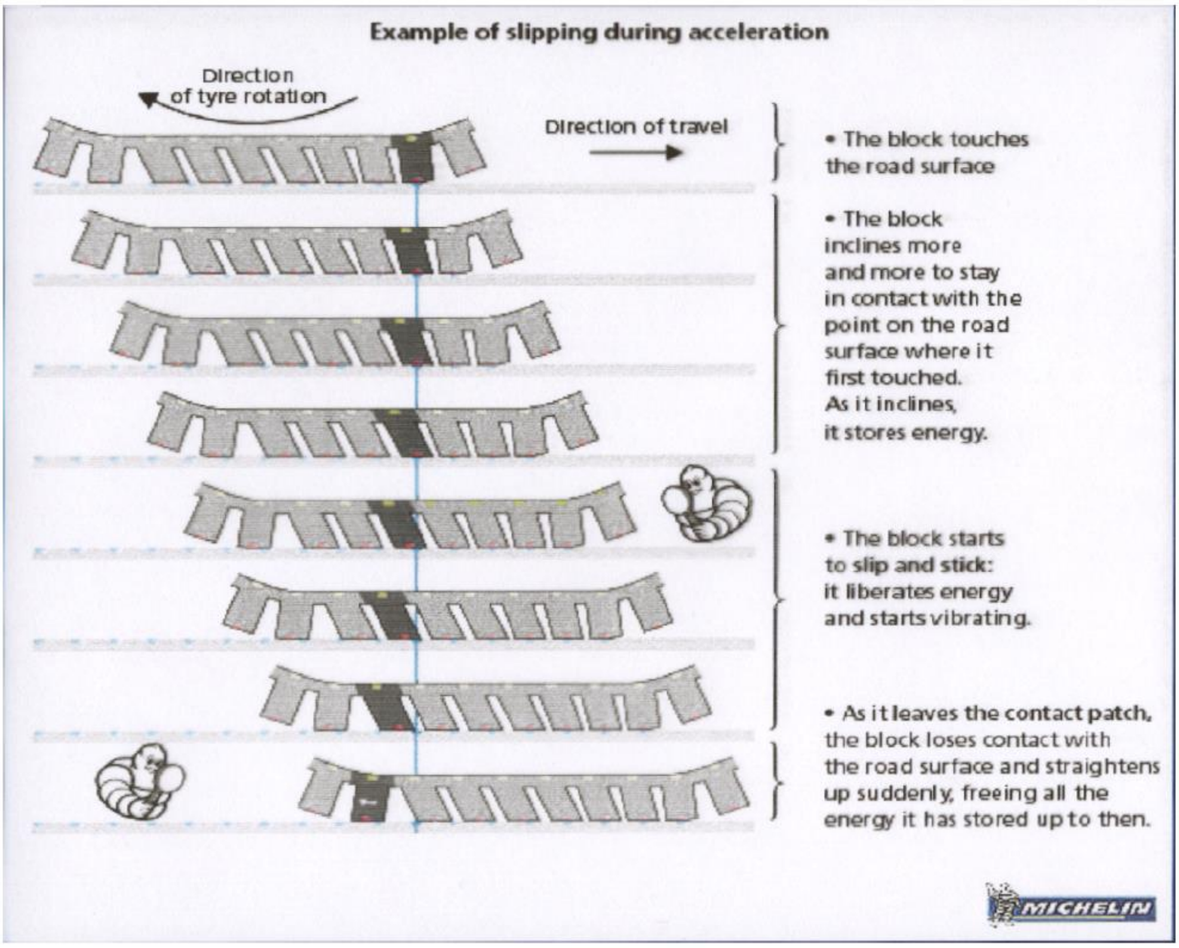
Each region has a specific rubber material with its own properties in order to guarantee that the tire will withstand the temperature and tensions under which it will be submitted.

To provide the market with a product that will meet its expectations, tire manufactures work hand-in-hand with vehicle manufacturers collecting data and information that guides the tire project.

2.2 Tire slip

To analyze tread movement, let's consider that the tread is composed by a series of rectangular blocks. Each block gradually touches the road surface and is submitted to a friction force creating a shearing tension as the tire moves. This longitudinal shear deformation of the tread is released as the tread leaves the contact area. However, this scenario only happens when the vehicle is at a constant velocity.

Figure 3 – Tread deformation and slip [3]



As the car accelerates, the shear solicitation increases to the point where the block starts to slip. This phenomenon can be seen in Figure 3.

In the same way, when the car brakes, the block is solicited by a shearing force in the opposite direction until the slipping of the tread occurs.

This slip, s, can be calculated using equation 1, where V_t is the tire's velocity and V_v is the vehicle's velocity [4]:

$$s = \frac{V_t - V_v}{\max(V_t, V_v)} \tag{1}$$

To help visualize this phenomenon, let's consider the extreme point of both situations: a car accelerating still and a braking car with the tires locked up while in movement.

In the first situation, the force provided by the wheel to the tire's contact area is much higher than the friction force, the tire slips and the car stays still. As for the equation, V_v is equal to zero and s is equal to 1.

For the braking car in movement, the car's momentum is large enough for the longitudinal force at the contact area to be much greater than the friction force. V_t is equal to zero and s is equal to -1.

2.3 Inflation pressure

Tire inflation is an important parameter that directly influences tire wear and safety driving. Figure 4 shows how the contact area geometry is influenced by tire inflation pressure:

Figure 4 – Tire's geometry due to inflation pressure [5]

When the tire is inflated in accordance with its design and usage, the whole tread band is in contact with the road, providing uniform wear and grip. On the other hand, for tires on the drive axle, when the tire is under inflated, irregular wear takes place and the shoulder region suffers more wear due to tire slip, causing an early disposal of the tire. When the tire is over-inflated, the center region suffers more wear.

Figure 5 – Irregular wear on drive tires caused by improper inflation [5]

This phenomenon, shown on Figure 5, is seen in tires on the drive axle. For tires on non-driving axles, if the tire is under inflated, the center region will suffer more wear due to route irregularities gradually sweeping away the rubber than the shoulder region due to contact area sliding. Likewise, the shoulder region will suffer more wear if the tire is over inflated.

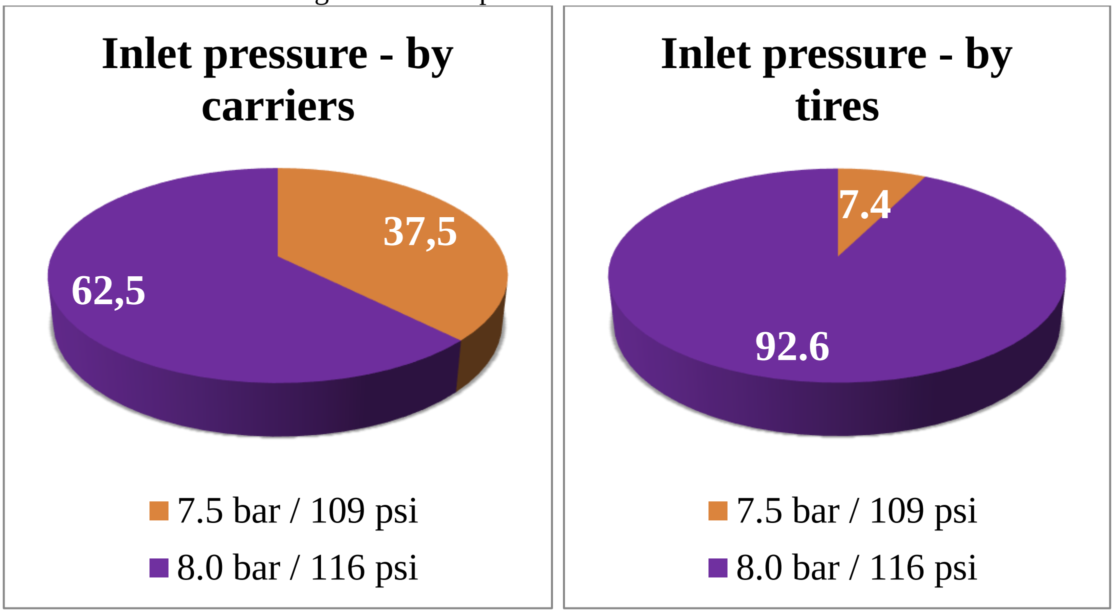
In addition to causing irregular wear and early disposal of the tire, the reduction of the tire’s contact surface on the road reduces grip, which means that driving safety is compromised. Therefore, it is of the utmost importance to inflate the tire at the correct pressure according to its design and usage.

3 USAGE RESEARCH

To have a better understanding of how the tires are used by the carriers, a survey form was created with the help of the university advisors and Michelin. See “Appendix A” for the complete form.

Eight carriers answered the survey. Their itineraries englobe all five regions of Brazil, with a greater density in the Southeast, Northeast and Center-West regions. In total, they have 3927 trucks with 9346 tires bought per year. 616 of those trucks are 4x2 trucks that were the object of study of Julia Coelho Santos’ work [1]. These trucks use 275/80 R22.5 tires.

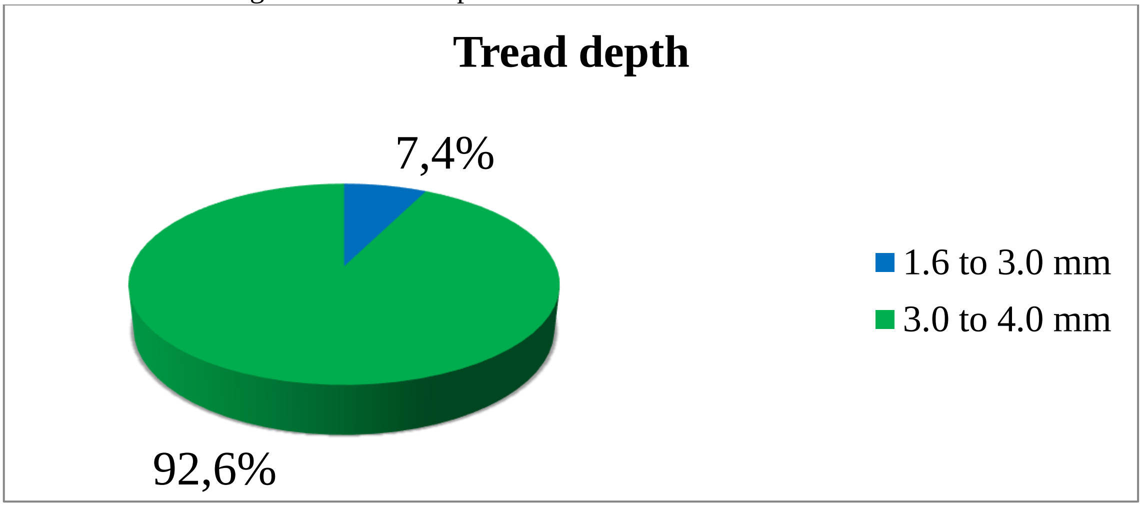
Figure 6 – Inlet pressure used for 275/80 tires



As it can be seen in Figure 6, the survey also showed that 62.5 % of the carriers use 8.0 bar of pressure on their tires against 37.5 % that calibrate at 7.5 bar, which is – like other companies – Michelin’s recommended value for 275/80 tires in regular use. If we consider the amount of trucks in each carrier, the percentage of 4x2 truck tires at 8.0 bar of pressure goes to 92.6 % against 7.4 % that are calibrated at 7.5 bar.

An interesting result is tire's tread depth at the first disassemble, before the first retreading.

Figure 7 – Tread depth at tire's take out before first retread



As showed in Figure 7, most tires are disassembled when its tread depth is between 3.0 mm and 4.0 mm, even though Brazilian legislation determines a minimum of 1.6 mm of tread depth. When asked why, companies respond that it is meant to avoid any kind of accident due to loss of performance.

Figure 8 – 4x2 truck configuration [6]

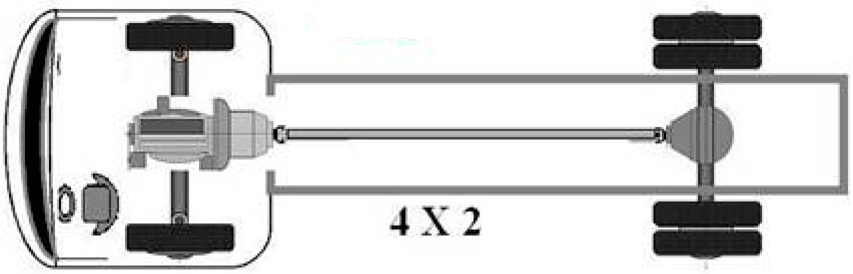
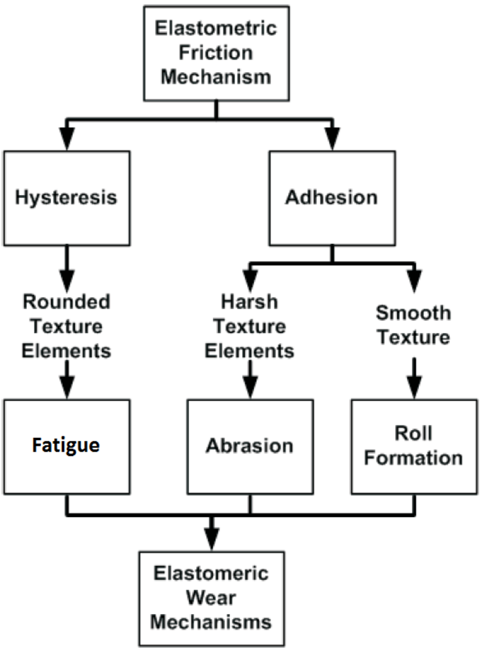


Figure 8 shows a scheme of the studied truck. The front axle of this type of truck is the steer axle while the rear axle is the drive axle, which provides torque.

4 WEAR

The wear of rubber is due to energy dissipation caused by friction [7]. On that account, tire wear can be divided into two main phenomena, as shown in Figure 9.

Figure 9 – Schematic diagram of the rubber wear mechanism [7]



Adhesion occurs when two solid surfaces slide over each other under pressure. Temporary bonding appears between the molecules of a sliding rubber surface and a contact surface due to the high pressure [7]. A sub-category of adhesion wear, abrasive wear, is caused by rubber sliding on the road surface during acceleration and braking.

Hysteresis wear is due to the tread being submitted to a shearing force during acceleration and braking. When a specific tread area is in contact with the road, this portion is compressed and submitted to a shearing force in the contact area. When it leaves the contact area, the tread is released. After a certain number of rotations, a portion of the tread reaches its fatigue limit and throws small particles of rubber onto the road. Hysteresis is considered to be a phenomenon within the sliding rubber [7].

Considering that a truck tire can have a lifespan of over 200.000 km, hysteresis can be an important factor for wear in a long-term perspective. However, this work will focus on abrasive wear, which is considered a more significant cause of tire wear in comparison to hysteresis [4].

In this sense, the main factors of tire wear are the forces that the tire is submitted to, material properties, road conditions, sliding distance and contact area.

4.1 Wear laws

Several wear models were proposed over the years, some theoretically, others empirically. However, few of them are publicly available. In this section, the most discussed models are presented.

Some of these models are more refined than others, taking into consideration more parameters, but they do have some of them in common, such as the applied force, material characteristics and the sliding distance – or the travelled distance.

4.1.1 Archard's wear law

Also known as Reye-Archard-Khrushchov wear law, this method was conceived thanks to the combined works of Theodor Reye, in 1860, John Frederick Archard, in 1956, and Mikhail Mikhailovich Khrushchov, in 1960. It is commonly used for metal disc wear.

The abrasive model of this law is as follows [3]:

$$V = \frac{F_N \cdot s}{H} \cdot k \tag{2}$$

where V is the volume of worn material, in mm^3, F_N is the normal force, in N, s the slip distance, in mm, H the material hardness, in N/mm^2, and k is the dimensionless wear coefficient.

Reye's hypothesis, or dissipative energy hypothesis, is then implemented in this model. This hypothesis states that the volume of material lost due to adhesive wear effects is proportional to the work performed by the friction forces [4]. Therefore, the normal force can be replaced by the longitudinal and lateral forces applied to the tire's contact area:

$$V = \frac{W_x + W_y}{H} \cdot k \tag{3}$$

,

$$W_x = F_x \cdot s_x \tag{4}$$

$$W_y = F_y \cdot s_y \tag{5}$$

where W_x is the longitudinal work, in N.mm, W_y is the lateral work, in N.mm, s_x is the longitudinal tire slip in mm and s_y is the lateral tire slip in mm.

The hardness of the material and the longitudinal and lateral slip distances are calculated using Finite Elements simulations from the software developed by Michelin at reference usage conditions. The applied forces come from the truck model.

The wear coefficient k is defined in the literature [8] as the wear volume fraction at the plastic contact zone:

$$k = \frac{V_w}{V_p} \tag{6}$$

where V_w is the worn volume and V_p is the volume of the plastically deformed zone.

In the literature [9], k is well defined for metallic materials and varies from 10^{-7} to 10^{-3} (table in "Appendix B"). There is no normalized value for rubber, but, since this work focuses on estimating the relative wear, k can be disregarded.

In order to have an idea of tread depth, instead of volume loss, let's divide equation 3 by the contact surface area, A, in mm^2, calculated by the Finite Elements software for each condition.

$$P = \frac{F_x \cdot s_x + F_y \cdot s_Y}{H \cdot A} \tag{7}$$

This formulation provides the height loss, P, in mm.

4.1.2 Schallamach's wear law

Adolf Schallamach developed this model while he was working for the British Rubber Producers' Research Association. Similar to Archard's equation, Shallamach's is defined as [3]:

$$Q = \gamma \cdot s \cdot F_N \tag{8}$$

where Q is the abrasive quantity, γ is the abrasion per unit of energy dissipation, s is the sliding distance and F_N is the normal force. The units, however, are not mentioned by Schallamach [3].

Schallamach's equation using Reye's hypothesis is as follows:

$$Q = F_x \cdot s_x + F_y \cdot s_Y \tag{9}$$

Similarly to k on Archard's equation, γ will be disregarded in this comparison.

4.1.3 Other wear laws

Another suggested approach for tire wear modelling can be represented as [10]:

$$V = \beta \cdot e^{\alpha t} \tag{10}$$

where V is the volume loss, α is a constant, t is time and β is an unknown term identified as "some characteristic of the initial surfaces".

In the literature, another suggested model is [10]:

$$\Delta W = K \cdot F^{a} \cdot V^{b} \cdot t^{c} \tag{11}$$

where ΔW is the weight loss, F is the applied load, V is the speed, t is time and K, a, b and c are empirical constants.

4.2 Sensitivity test

Before analyzing the FEM results, let's visualize how each theoretical model behaves in terms of tire wear with the variation of applied force in Figure 10, sliding distance in Figure 11, material hardness in Figure 12 and contact surface are in Figure 13.

Figure 10 – Applied force [daN] x Tire wear rate

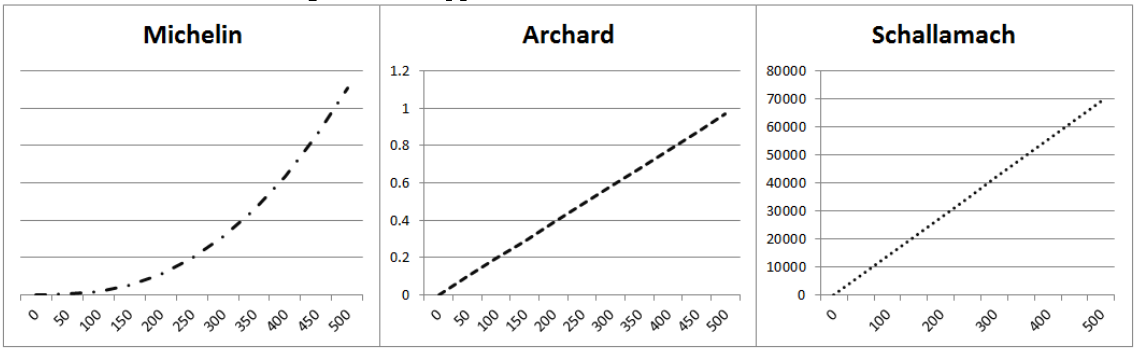


Figure 11 – Sliding distance [mm] x Tire wear rate

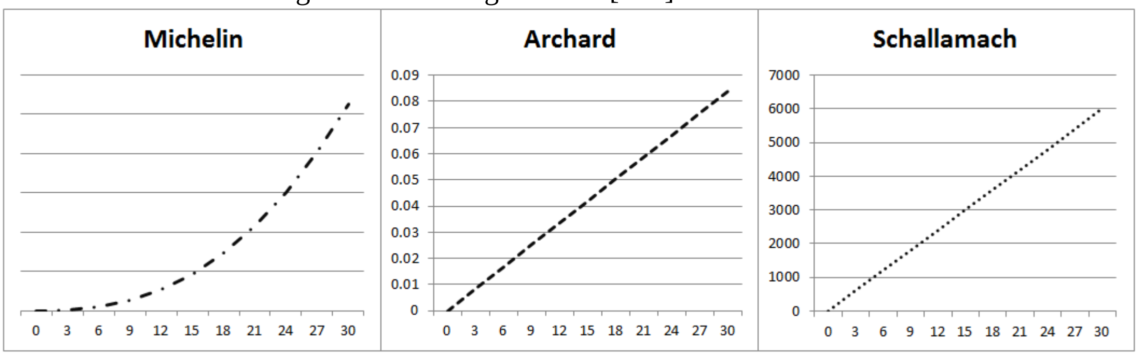


Figure 12 – Material hardness [N/mm2] x Tire wear rate

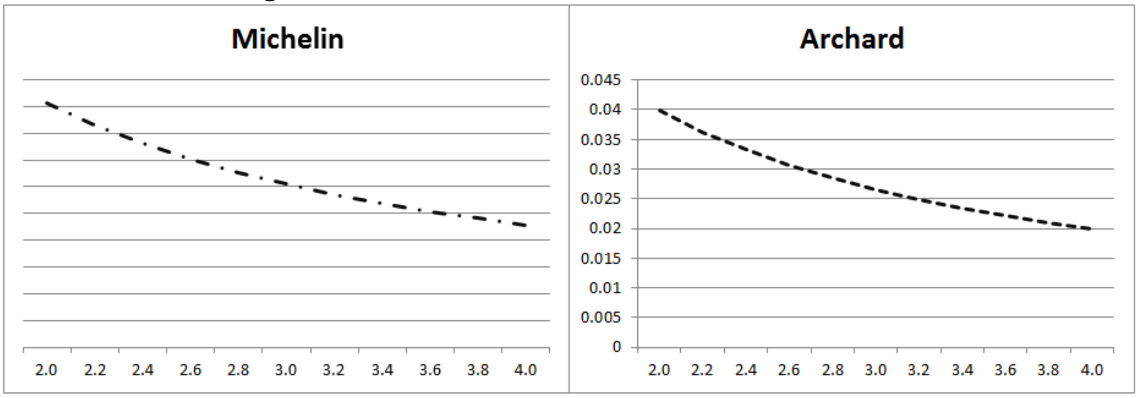
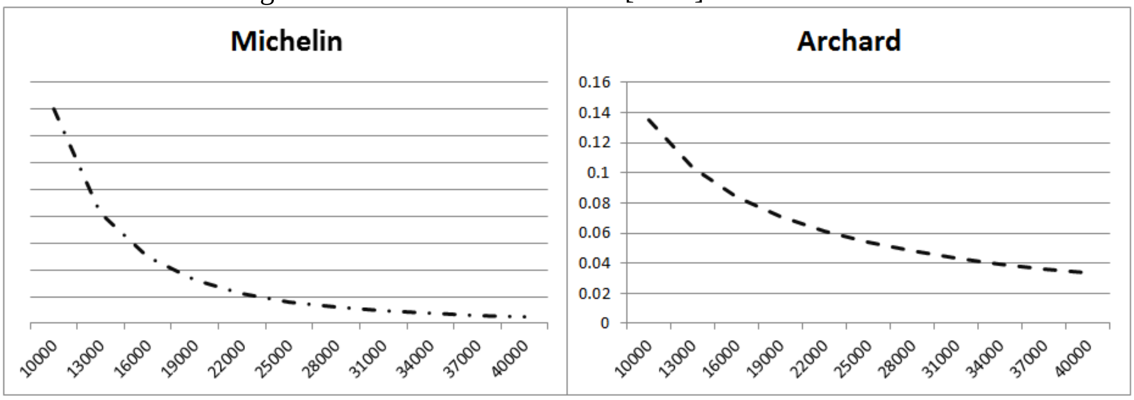


Figure 13 – Contact surface area [mm2] x Tire wear rate



Tire wear rate for Michelin's and Archard's model is in mm per wheel turn. Schallamach's model, as discussed before, estimates a wear quantity, not specifying its unit. For confidential reasons, Michelin's wear rate values are not displayed.

For applied force and sliding distance, Figure 10 and Figure 11, Archard's and Schallamach's equations have the same tendency in terms of wear rate. Michelin's equation also increases the wear rate, but with different curve coefficients. Since Shallamach's equation is simpler, with less parameters involved, its comparison stops at the sliding distance, in Figure 11.

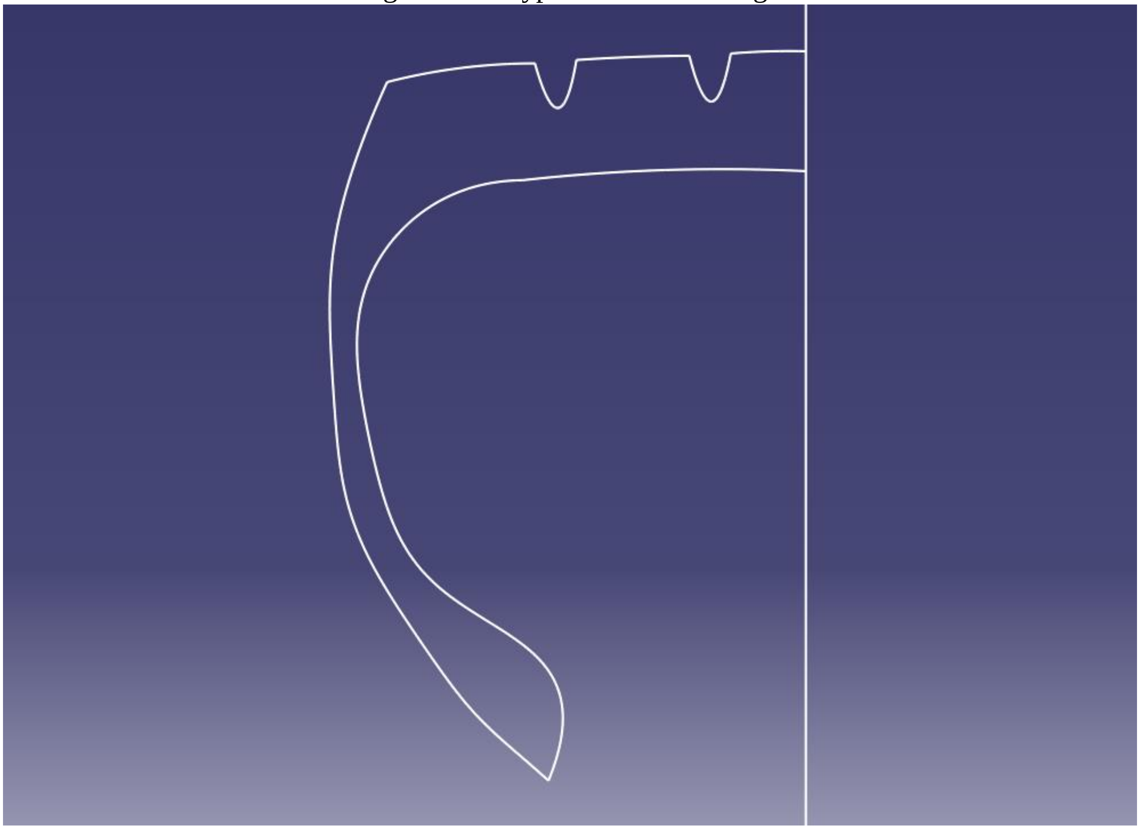
When analyzing the material hardness variation in Figure 12, Archard's equation shows the same tendency as Michelin's equation. For the contact area, in Figure 13, they have close responses, but with different curve coefficients.

5 METHODOLOGY

Using the Finite Elements software developed by Michelin, a tire's concept can be simulated before its production in order to anticipate the tire's performance and behavior. The mesh is created from a 2D design of the tire. Then, the materials that compose the tire are chosen from a library that provides us with their properties. Finally, the 2D mesh is revolutionized to form the 3D design of the tire and the simulation begins. To create the analyses, two 275/80 R22.5 tires were considered.

To explain how tire's simulations are made, Figure 14 displays a hypothetical tire design. An actual tire design must indicate all inside structures.

Figure 14 – Hypothetical tire design



From this 2D design, the mesh is created, the tire is divided in several elements, boundary conditions are defined and each structure – metal and rubber – is specified in terms of material properties. Figure 15 also displays a hypothetical tire mesh. An actual tire mesh must take into account all structures showed in Figure 2.

The boundary conditions are the contact surface with the road, in light blue, the contact surface of the tire to the wheel, in pink, and the inner pressure region of influence, in yellow.

Figure 15 – Hypothetical tire mesh

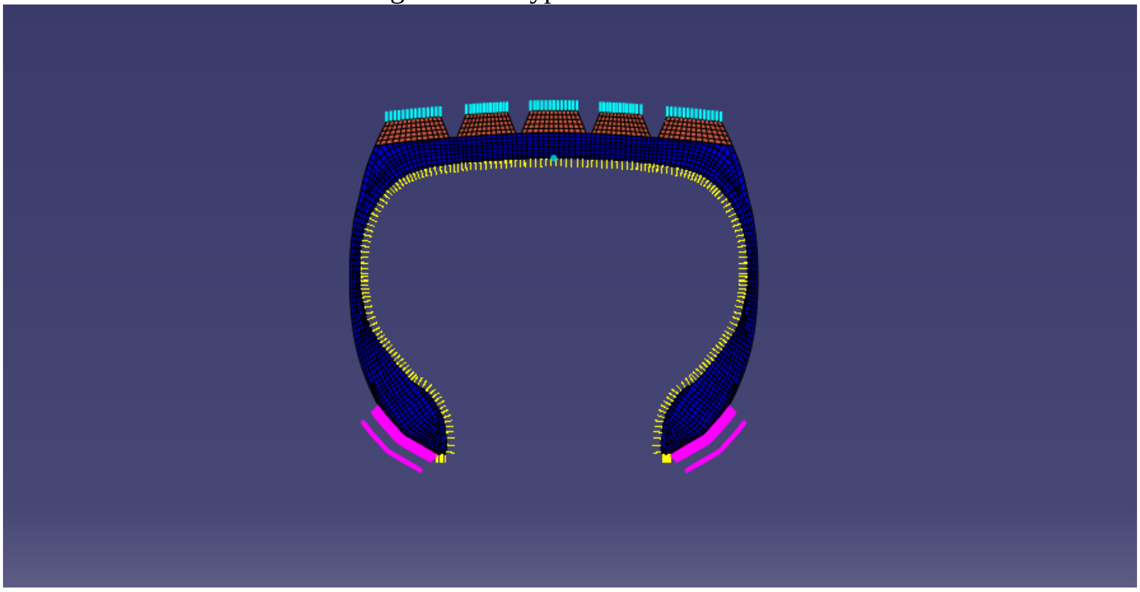
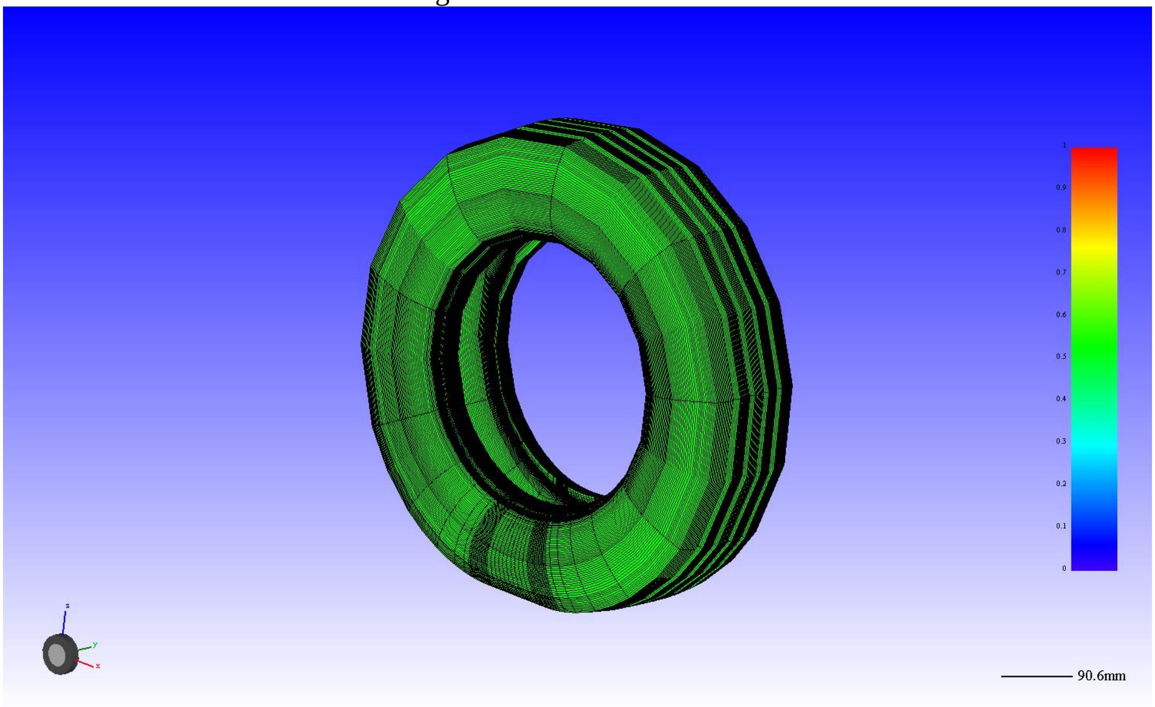


Figure 16 – Tire’s 3D view



As seen in Figure 16, the tire is divided into different sections before running the FEM simulation. However, the contact area is split into much smaller sections to provide a more accurate result, since it is the most important region in terms of tire performance.

Hypotheses are:

- The simulated route is a flat asphalted ground with a friction coefficient;
- There are no irregularities on the road (holes, barriers, etc.);
- All models focus on the tire's overall wear, not distinguishing tread band regions;
- Road contact, wheel contact and inner pressure incidence as boundary conditions;
- Simulations done in a transient-state;
- No camber imposed.

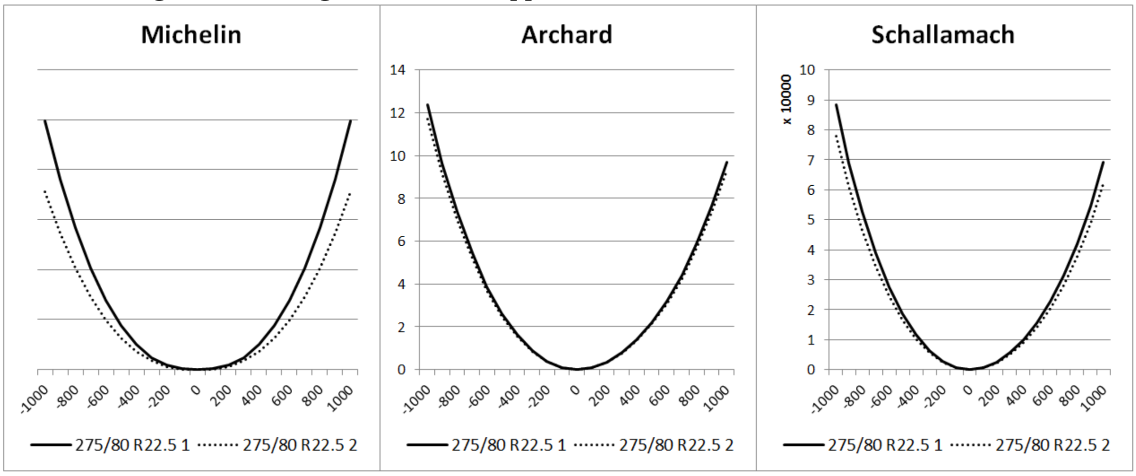
5.1 Wear rate curves

Another comparison can be made by plotting a curve of wear rate with the applied force variation for specific usage condition. This type of curve shows how the tire behaves under different applied forces.

The curves in Figures 17, 18, 19 and 20 represent the wear rate difference for each 275/80 R22.5 tire taking into account Michelin's, Archard's and Schallamach's models. The amount of wear estimated is not considered a true absolute estimation since k and γ parameters for Archard's and Schallamach's equations, respectively, are unknown. This comparison is only applicable in a relative perspective between tires and conditions.

For this comparison, simulations for each tire are made in order to determine material hardness and contact area reference values. To find out the sliding distance, a condition for each applied force is simulated. Out of interest, each F_x curve took 42 simulation steps while each F_y curve took 54 simulation steps. One step for each simulated condition.

Figure 17 – Longitudinal force applied [daN] x Wear rate [mm/wheel turn]



For longitudinal forces, the result in Figure 17 shows a reduction of 28% on wear rate from tire 1 to tire 2 using Michelin's model, 4% using Archard's model and 11% using Schallamach's model. However, all three wear models show that the wear rates of both tires are almost equal for low F_x values, as seen in Figure 18:

Figure 18 – Longitudinal force applied [daN] x Wear rate [mm/wheel turn]

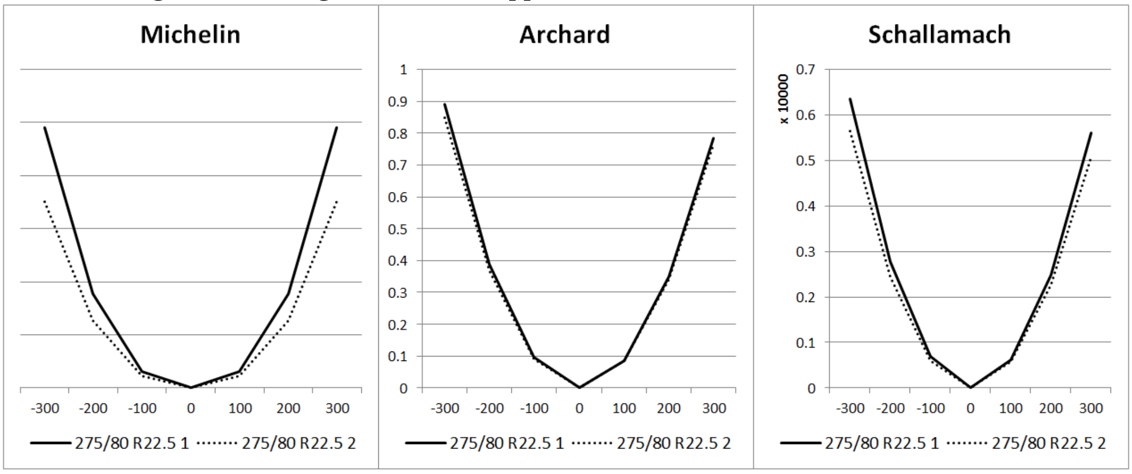
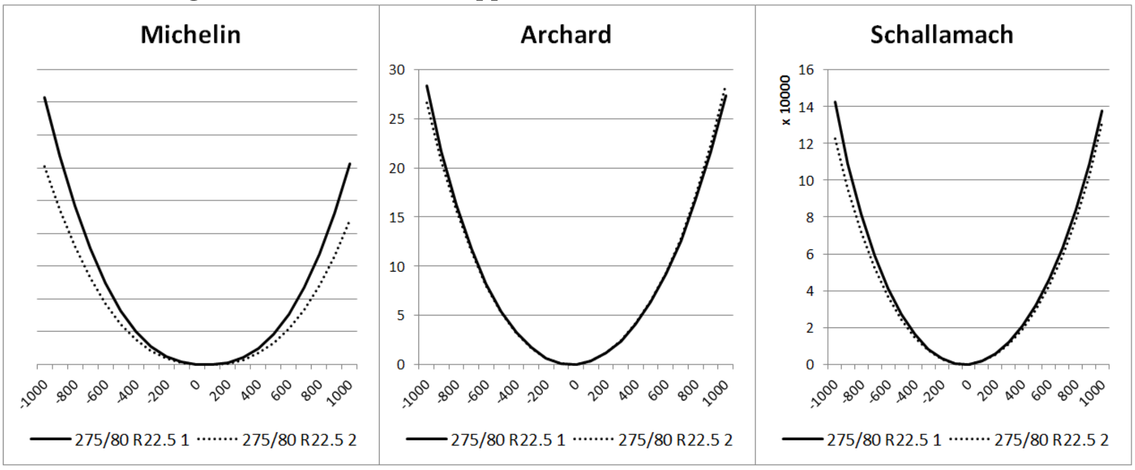


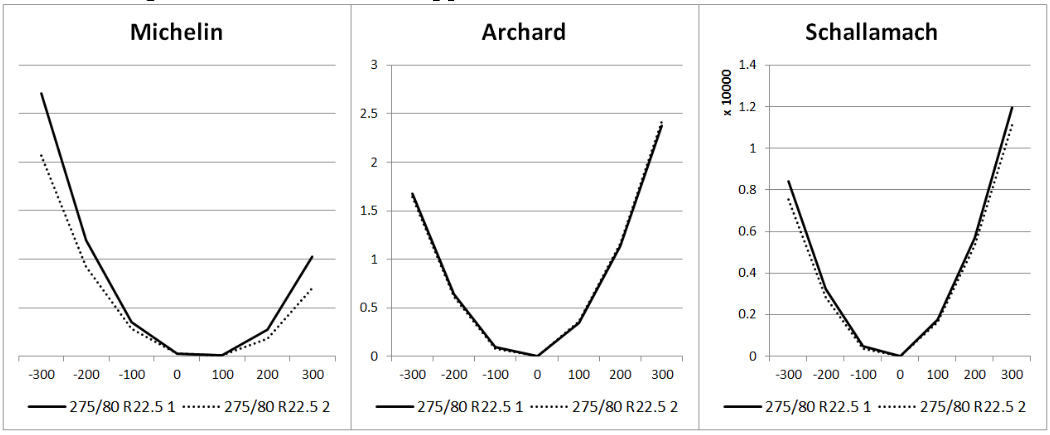
Figure 19 – Lateral force applied [daN] x Wear rate [mm/wheel turn]



For lateral forces, the result in Figure 19 shows a 28% reduction of wear from tire 1 to tire 2 using Michelin's model, 1% using Archard's model and 9% using Schallamach's model. However, Archard's model shows that for positive F_y values the wear of tire 2 is greater than the wear of tire 1. Figure 20 shows the same curves for low F_y values.

However, as explained previously, Schallamach's units are not defined by the author. Its unit for wear rate could only be defined as wear quantity per wheel turn. For confidential reasons, Michelin's wear rate values are not displayed.

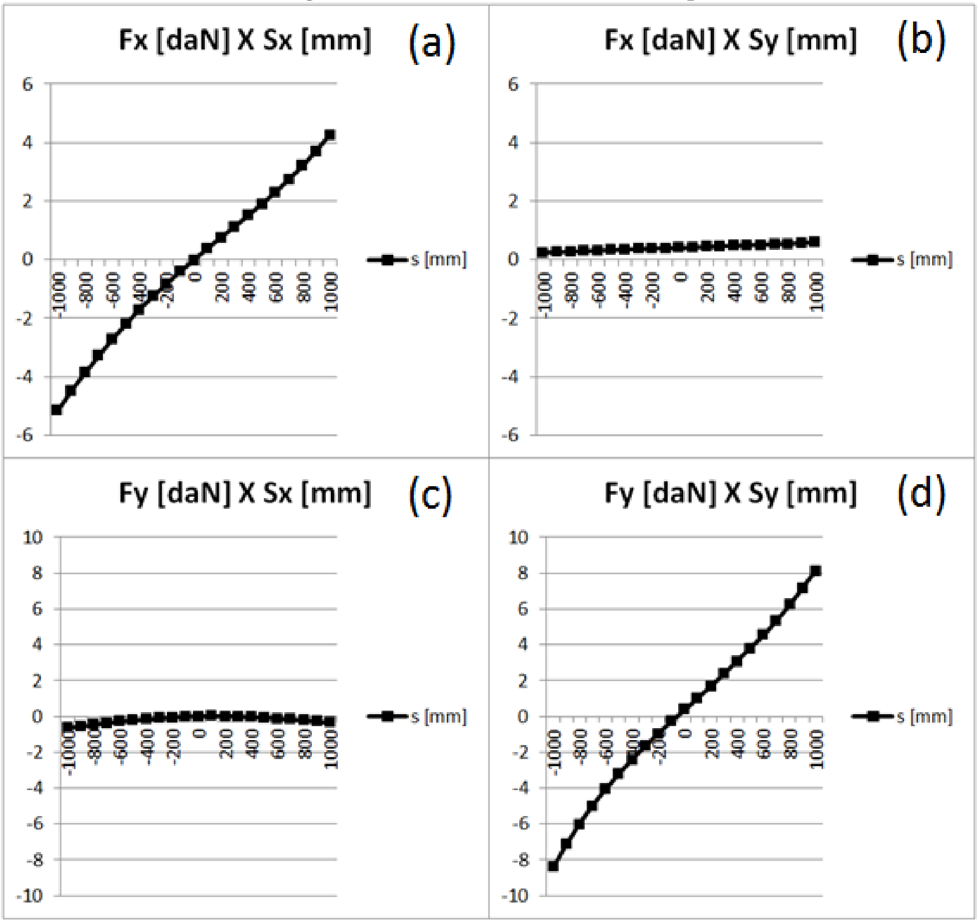
Figure 20 – Lateral force applied [daN] x Wear rate [mm/wheel turn]



5.2 Parameters influence

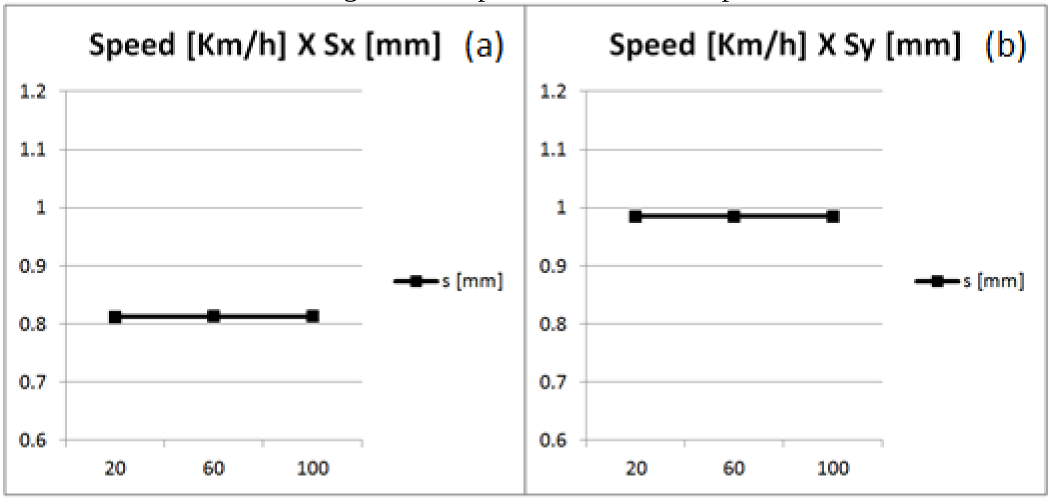
The output of the truck model includes the longitudinal, F_x, lateral, F_y, and vertical, F_z, forces applied to the tire's contact area and the vehicle's speed. To create the FEM database, a study was developed to find out how these parameters influence the slip distance.

Figure 21 – Forces influence on slip



FEM simulations, in Figure 21, show that the longitudinal force has little influence on the lateral slip – Figure 21 (b) – when compared to its influence on the longitudinal slip – Figure 21 (a). The result also shows that the lateral force has little influence on the longitudinal slip – Figure 21 (c) – when compared to its influence on the lateral slip – Figure 21 (d). The slip calculated is the slip within the contact area length that is on average 195 mm for the two studied tires.

Figure 22 – Speed influence on slip



For the speed, it is clear that velocity variation has no influence on longitudinal – Figure 22 (a) – or lateral slip – Figure 22 (b). With this in mind, the model database is divided into two groups: longitudinal force influence with vertical force variation and lateral force influence with vertical force variation.

The vertical force influence is a defining factor prior to the longitudinal and lateral forces influence.

5.3 Database

Considering the study carried out in the last section and the values of the truck model output, a database was created by varying the forces as indicated in Table 1.

Table 1 – Database force range in decanewton (daN)

Fz	**1000**		**1500**		**2000**		**2500**		**3000**		**3500**	
		-500		*-500*		*-500*		*-500*		*-500*		*-500*
		-400		*-400*		*-400*		*-400*		*-400*		*-400*
	-300	*-300*	*-300*	*-300*	*-300*	*-300*	*-300*	*-300*	*-300*	*-300*	*-300*	*-300*
	-200	*-200*	*-200*	*-200*	*-200*	*-200*	*-200*	*-200*	*-200*	*-200*	*-200*	*-200*
	-100	*-100*	*-100*	*-100*	*-100*	*-100*	*-100*	*-100*	*-100*	*-100*	*-100*	*-100*
	0	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
	100	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*
	200	*200*	*200*	*200*	*200*	*200*	*200*	*200*	*200*	*200*	*200*	*200*
	300	*300*	*300*	*300*	*300*	*300*	*300*	*300*	*300*	*300*	*300*	*300*
	400	*400*	*400*	*400*	*400*	*400*	*400*	*400*	*400*	*400*	*400*	*400*
		500		*500*		*500*		*500*		*500*		*500*
	Fx	**Fy**	**Fx**	**Fy**	**Fx**	**Fy**	**Fx**	**Fy**	**Fx**	**Fy**	**Fx**	**Fy**

Each cell of Table 1 is a Finite Element simulation that provides the slip value and each column has reference values for surface area and hardness modulus. Depending on the condition defined by the truck model output, the tire model creates iterations to find out the appropriate parameter values in order to estimate the wear. The force ranges were chosen based on the limitations of the truck model [1].

Slip values for tires 1 and 2 vary at 7.5 bar as shown in Figure 23 and Figure 24.

Figure 23 – Longitudinal slip [mm] by varying F_x [daN] at 7.5 bar

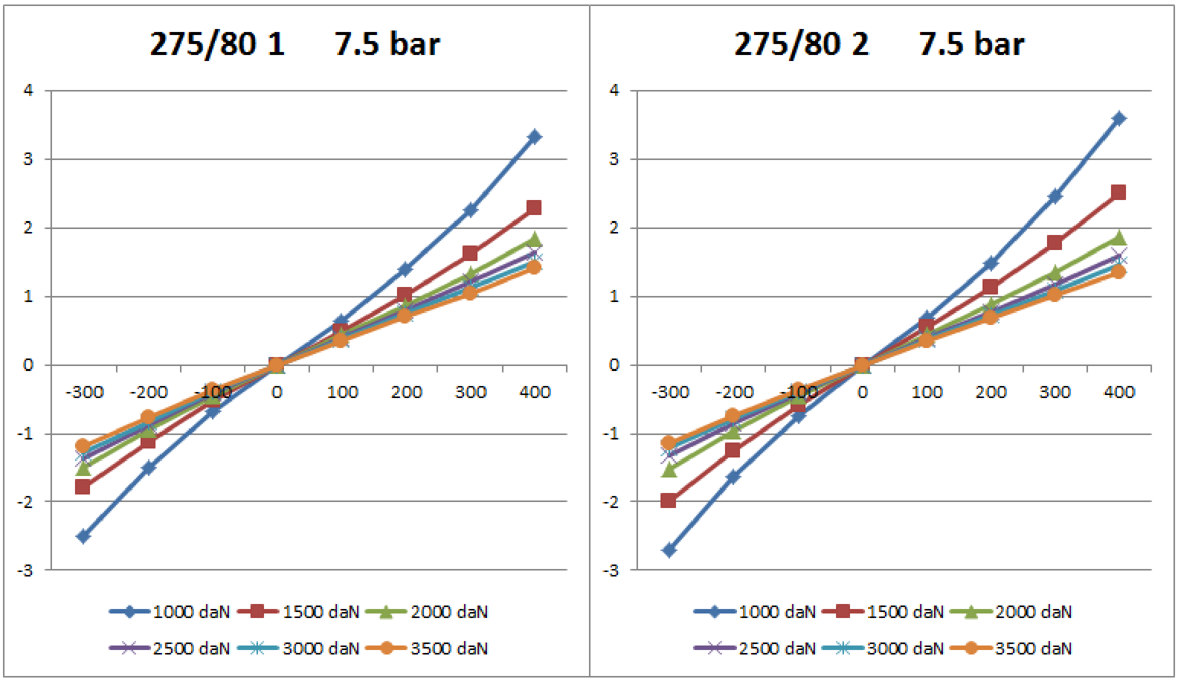
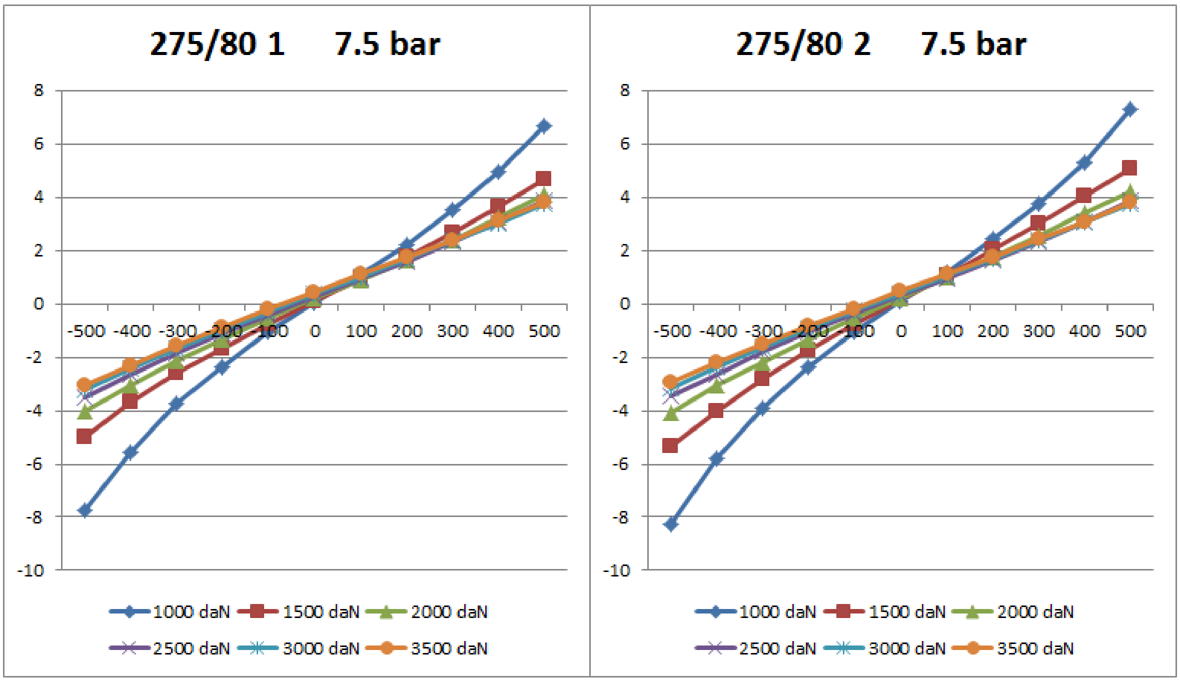


Figure 24 – Lateral slip [mm] by varying F_y [daN] at 7.5 bar



Slip values for tires 1 and 2 vary at 8.0 bar as shown in Figure 25 and Figure 26.

Figure 25 – Longitudinal slip [mm] by varying F_x [daN] at 8.0 bar

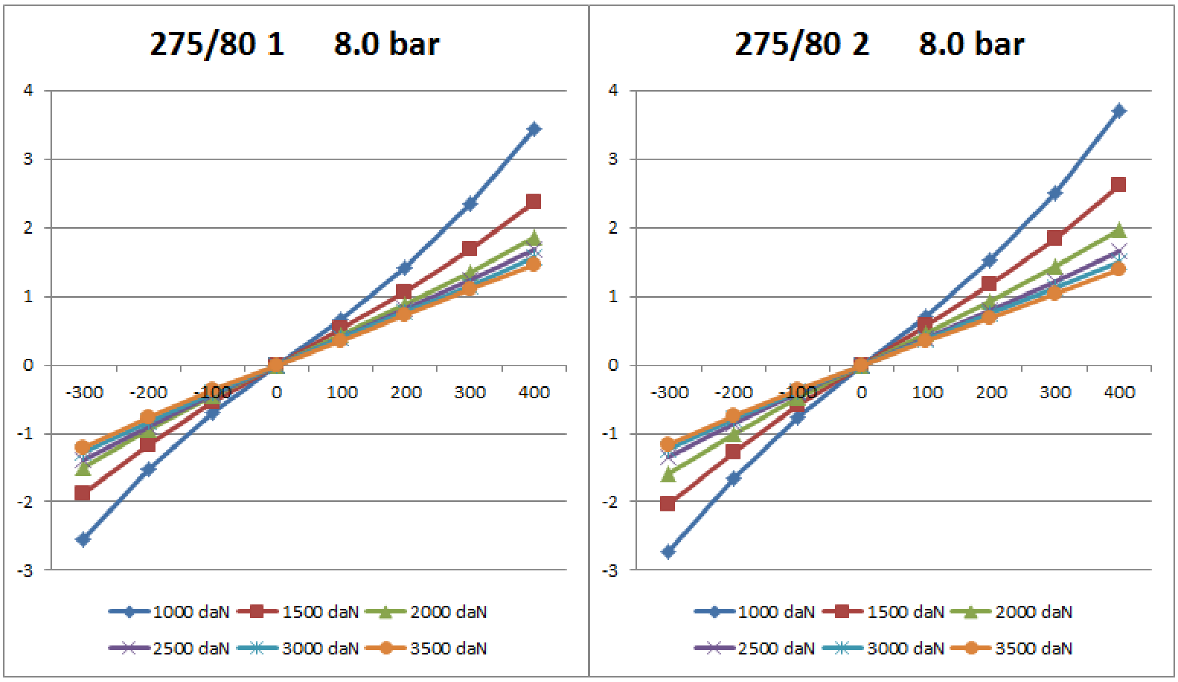
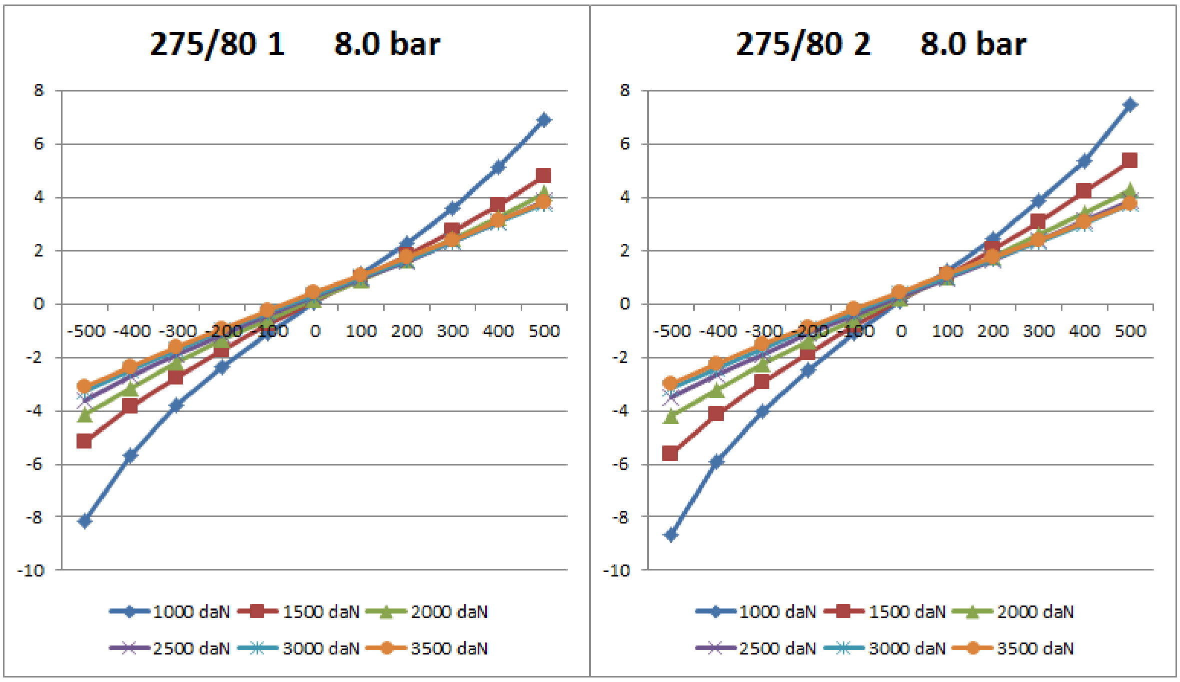


Figure 26 – Lateral slip [mm] by varying F_y [daN] at 8.0 bar



Considering the results presented in Figures 23, 24, 25 and 26, it is clear that the lateral force has a more important influence on tire slip than the longitudinal force when comparing the same amount of applied force. It can also be seen that the increase of the vertical force reduces tire slippage. However, in actual usage, the heavier the vehicle, the more longitudinal force is needed to overtake the friction force and move the vehicle.

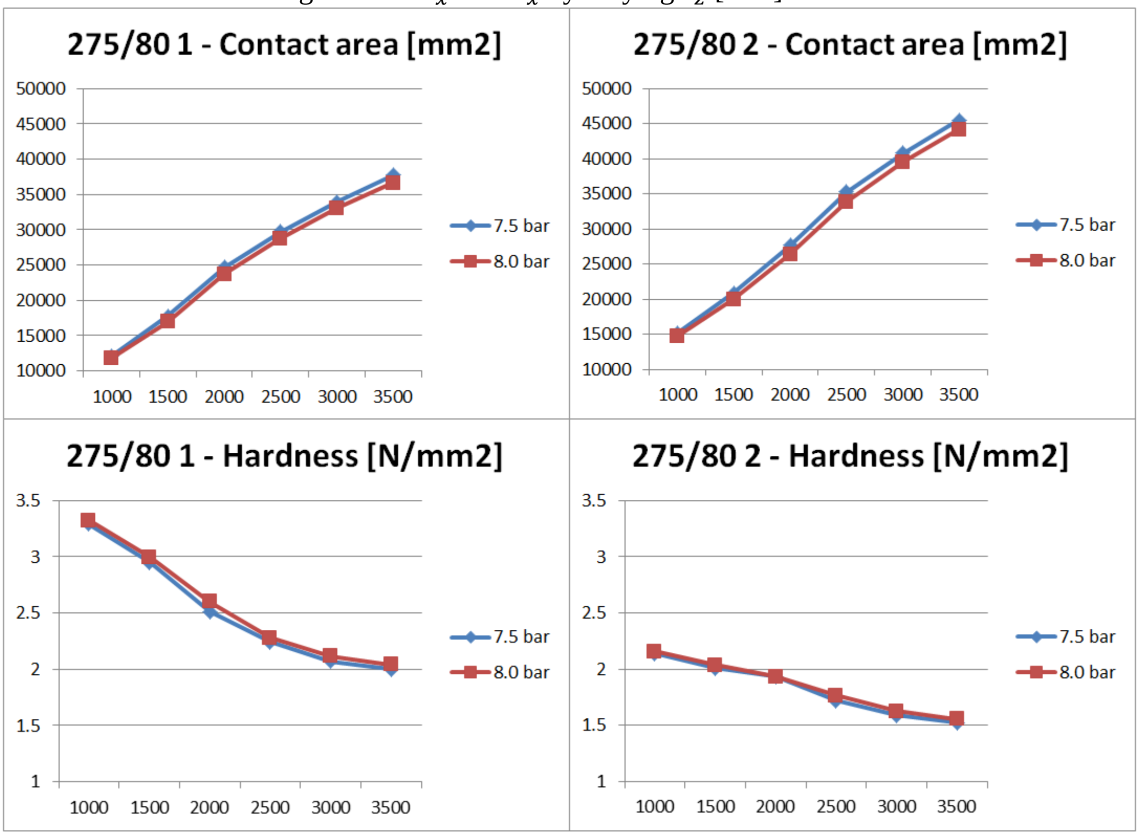
Surface area and hardness modulus also come from a reference condition for each F_z value. Since it would be unmanageable to calculate the contact area and hardness modulus for every possible combination of F_x and F_y values, this work proposes to use a reference condition for wear caused by the longitudinal force and another reference condition for wear caused by the lateral force. Thereby, equation 7 of Archard's model is modified to equation 12.

$$P = \frac{F_x \cdot s_x}{H_x \cdot A_x} + \frac{F_y \cdot s_Y}{H_y \cdot A_y} \tag{12}$$

Schallamach's equation is not affected.

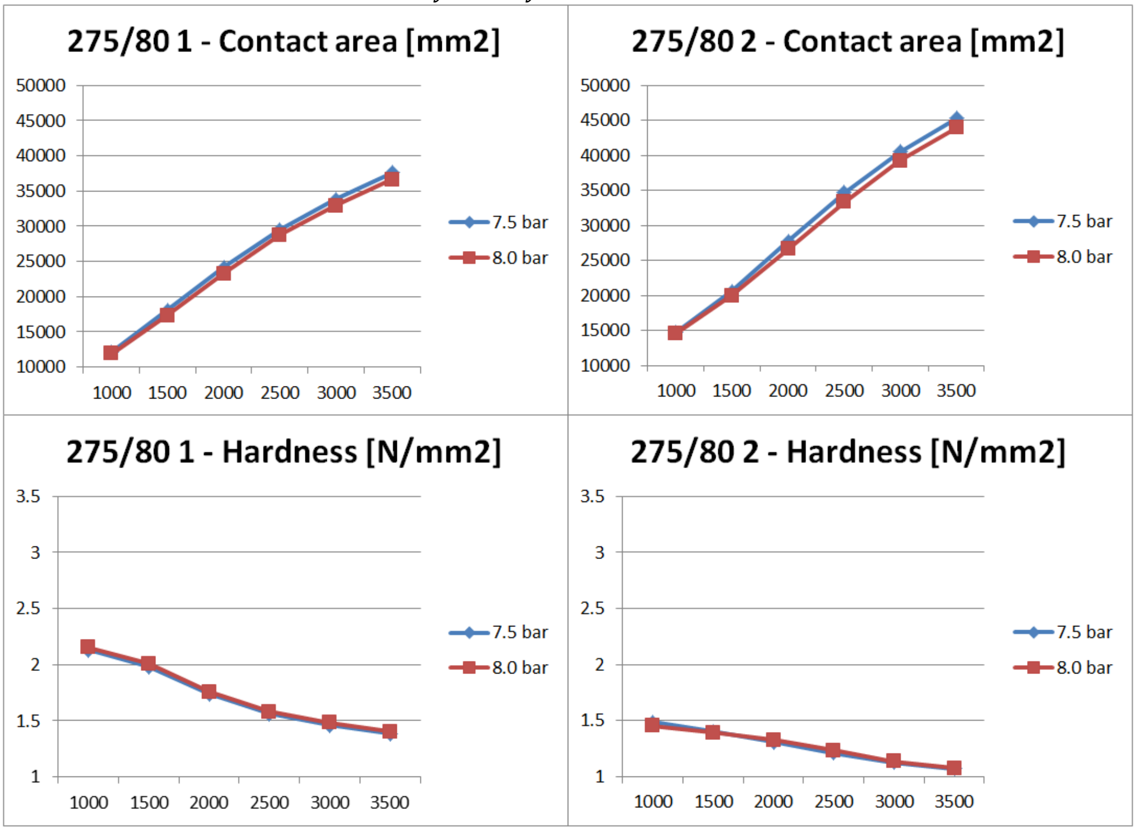
The results in Figure 27 for the contact area, A_x, and the hardness modulus, H_x, were obtained using a reference F_x and zero F_y:

Figure 27 – A_x and H_x by varying F_z [daN] values



The results in Figure 28 for the contact area, A_y, and the hardness modulus, H_y, were obtained using zero F_x and a reference F_y:

Figure 28 – A_y and H_y by varying F_z [daN] values



At first glance, it is clear that the applied vertical force, F_z, directly influences both the contact area and the hardness modulus, as seen in Figure 27 and Figure 28. The inflation pressure also has an impact on both parameters. Its increment of 0.5 bar slightly reduces the contact area and increases the hardness modulus for most scenarios. An interesting phenomenon is that, for both tires, the contact area difference between the two pressures seems to increase as the applied vertical force is augmented.

To create this database for each tire at each inflation pressure, it took about 120 steps for longitudinal wear and 210 steps for lateral wear values. In total, 660 steps for both tires at both inflation pressures. Each step is a simulated condition at the FEM software. In spite of this, once the simulations are done, the procedure developed to analyze and organize the results is practical and systematic.

6 MATLAB WEAR MODEL

In order to estimate the tire wear caused by the usage conditions from the truck model [1], two algorithms were created on MATLAB: one to determine the parameters values for each condition, provided by the FEM database, and another to calculate the wear for each wear model. The first code takes about 13 seconds to run while the second code takes about 22 seconds to run at a 16GB of RAM computer with an Intel Core i7 processor. The algorithms are presented in “Appendix C”.

The truck model outputs obtained for 4x2 trucks determine the parameters values for each condition that come from the database. To find out the estimated values of these parameters, a series of interpolations takes place and the values are allocated to be used on Michelin’s, Archard’s and Schallamach’s models.

4x2 trucks have six tires: two in the front and four in the rear. The truck model considers that both front tires suffer the same efforts and that the four rear tires also suffer the same efforts. That being said, front tire results are the same for both front tires and rear tire results are applicable to the four rear tires, considering that all tires are the same model and have the same inflation pressure.

The model does not take into consideration the differences on worn regions between drive axle tires from steer axle tires, explained in section 2.3, since the total tire wear is estimated, not distinguishing ribs.

Since the appearance of tire 1 and tire 2 results are not so different when analyzing wear graphs, let’s analyze the wear results for tire 1 and, afterwards, compare both tires.

6.1 Archard's results

Figure 29 – Front axle applied forces from truck model

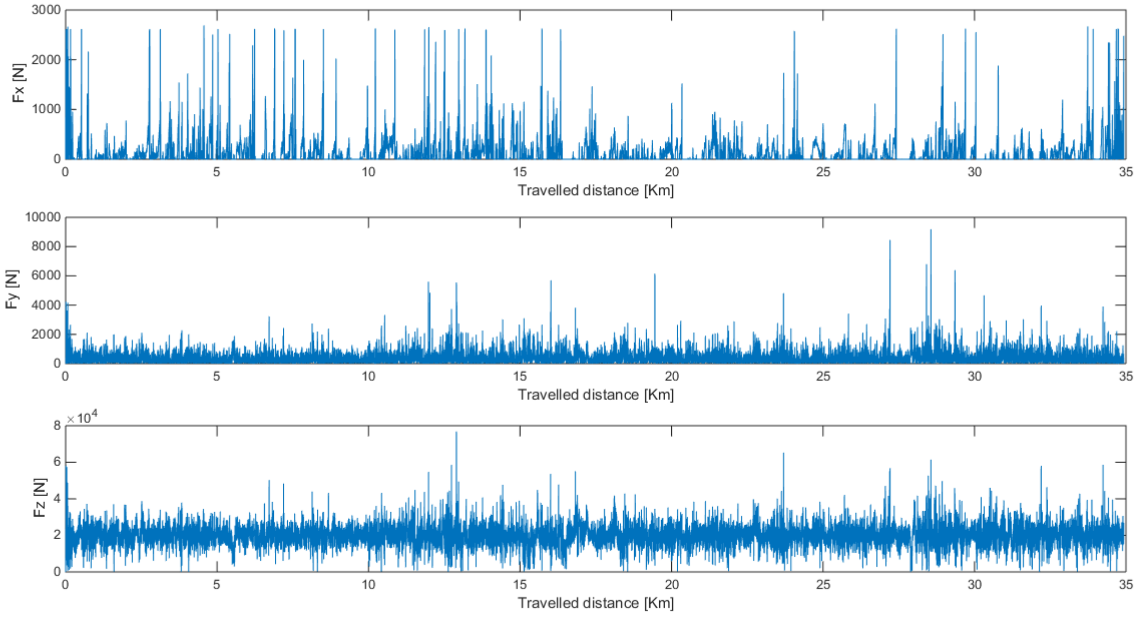


Figure 30 – Archard's wear estimation for tire 1 at the front axle

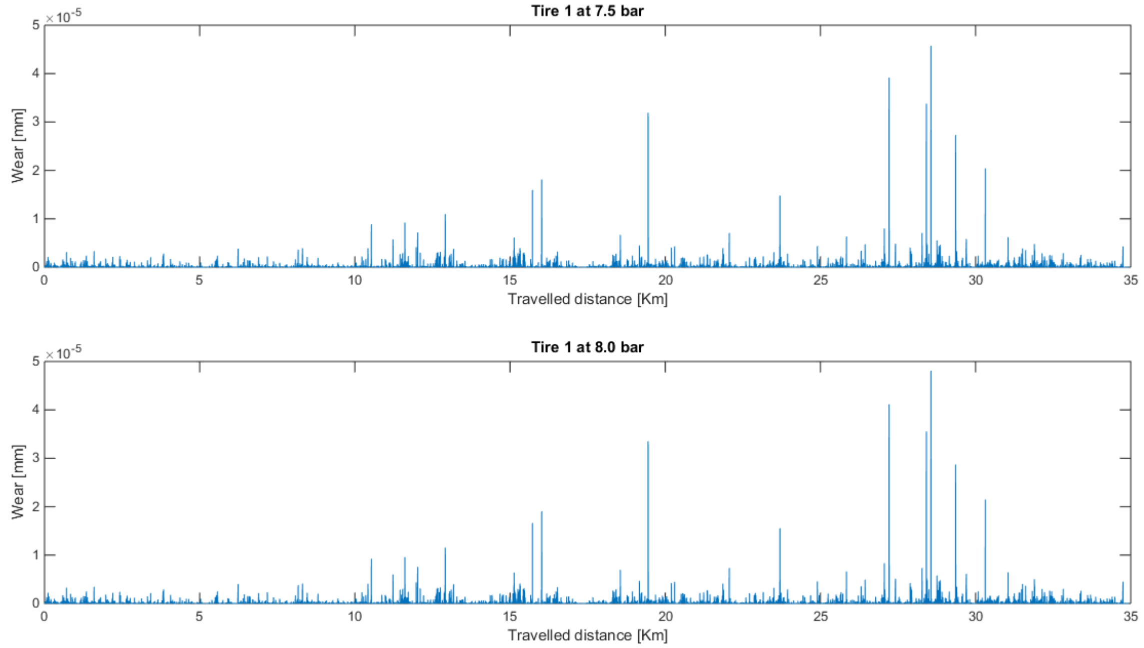


Table 2 – Archard's wear estimation for front tires

Wear	X [mm]	Y [mm]	Total [mm]
7.5 bar	0.0002069	0.0026594	0.0028663
8.0 bar	0.0002200	0.0027973	0.0030174

Figure 29 shows the applied forces at the front axle tires while Figure 30 shows the tire wear estimation for tire 1 at the front axle in mm during the 35 km route. However, as explained before, this is not a correct absolute estimation since the wear coefficient k is unknown.

As it can be seen in Table 2, wear caused by lateral slip takes more than 93% of total wear – more than 10 times the longitudinal wear estimation. It is also clear that the model shows an increase on wear when the tire is over inflated for both longitudinal and lateral wear.

When analyzing the force values coming from the truck model, the correlation between lateral force variations with tire wear estimation becomes evident. The wear values peaks in Figure 30 are due to the peaks of the lateral force values in Figure 29.

Figure 31 – Rear axle applied forces from truck model

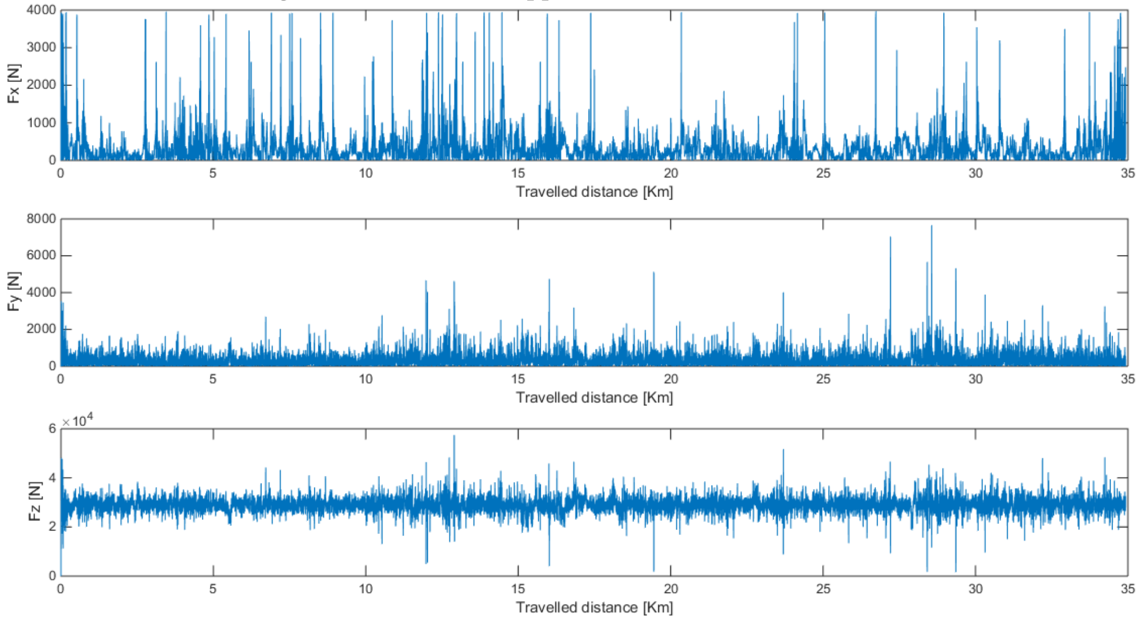


Figure 32 – Archard's wear estimation for tire 1 at the rear axle

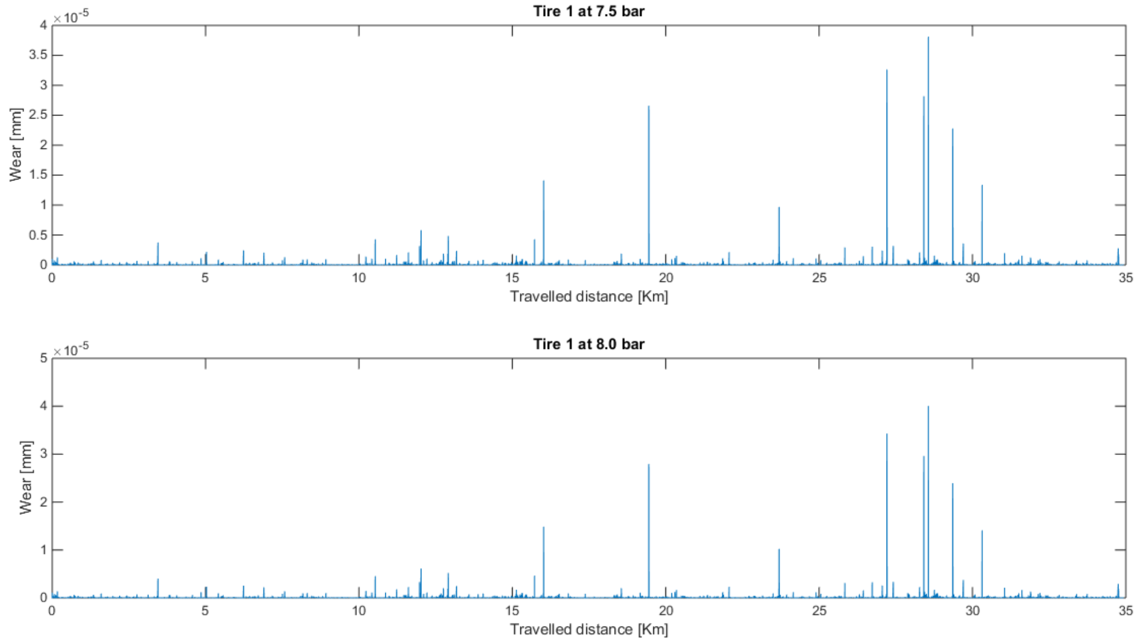


Table 3 – Archard's wear estimation for rear tires

Wear	X [mm]	Y [mm]	Total [mm]
7.5 bar	0.0003651	0.0009141	0.0012792
8.0 bar	0.0003850	0.0009445	0.0013295

In much the same manner, the tire wear estimation for rear tires shows a greater importance of lateral wear on the overall wear of the tire – over 71% – as seen in Table 3. Once again, a correlation between lateral force variations in Figure 31 with tire wear estimation in Figure 32 is clear.

It is also clear that longitudinal forces in the rear axle, shown in Figure 31, are greater than longitudinal forces in the front axle, shown in Figure 29, and that lateral forces in the rear axle, shown in Figure 31, are smaller than lateral forces in the front axle, shown in Figure 29. For the vertical forces, the average value is greater in the rear axle, shown in Figure 31. However, the peak values are greater in the front axle, shown in Figure 29.

6.2 Schallamach's results

Figure 33 – Schallamach's wear estimation for tire 1 at the front axle

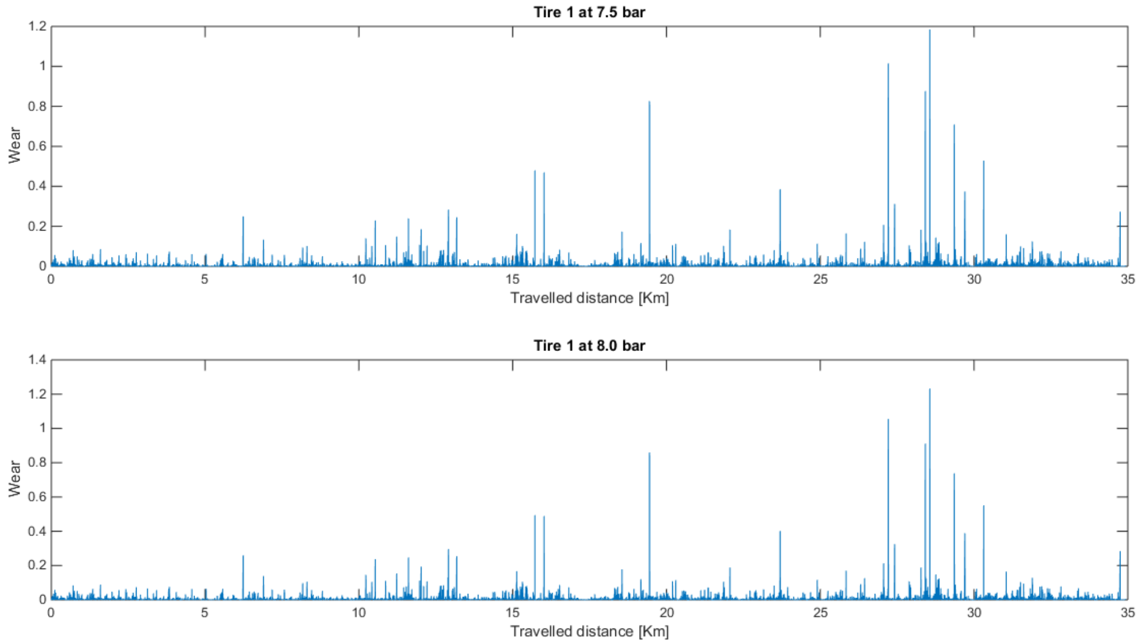


Table 4 – Schallamach's wear estimation for front tires

Wear	X	Y	Total
7.5 bar	12.431146	80.616537	93.047683
8.0 bar	13.038574	83.818717	96.857291

As for Schallamach's model, front tires lateral wear takes about 87% of the total wear as seen in Table 4. An increase on tire wear due to over inflation can also be seen at this model. As seen before for Archard's model, wear peaks in Figure 33 are correlated to lateral force peaks at front tires in Figure 29.

Analogously to Archard's model, wear values are not valid absolute estimations since the γ coefficient is unknown. These results can only be used in a relative perspective.

Figure 34 – Schallamach's wear estimation for tire 1 at the rear axle

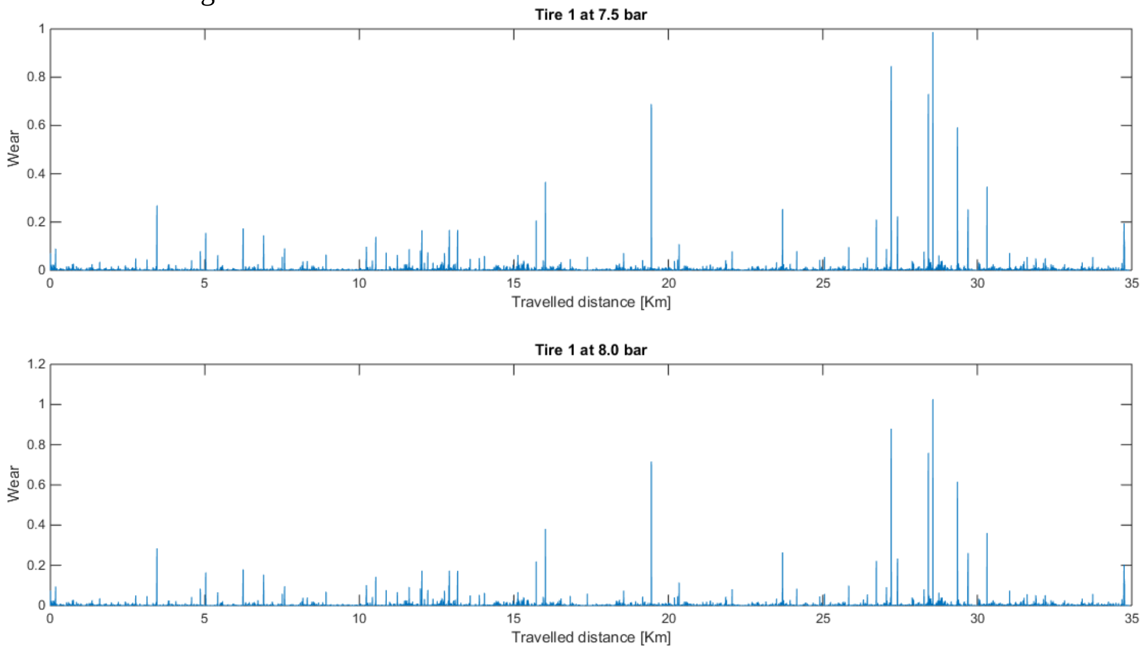


Table 5 – Schallamach's wear estimation for rear tires

Wear	X	Y	Total
7.5 bar	25.330201	38.042737	63.372938
8.0 bar	26.462306	38.571536	65.033842

When analyzing rear axle tires, the same phenomenon occurs with approximately 60% of the overall wear coming from lateral wear, as seen in Table 5. The wear peaks in Figure 34 are also correlated to the lateral force peaks for rear axle tires in Figure 31.

6.3 Michelin's results

Michelin's model also shows an increase on tire wear due to over-inflation, as it will be discussed in the next section. It also shows that 71% of the total wear is caused by lateral forces for front tires. However, for rear tires, it shows that lateral wear only causes 27% of the total wear.

The results are not displayed for confidential reasons.

6.4 Global results

Table 6 shows how the increase of tire inflation pressure from 7.5 bar to 8.0 bar changed the amount of estimated wear:

Table 6 – Inflation pressure results

7.5 bar → 8.0 bar					
275/80 1					
Front tires			**Rear tires**		
Michelin	Archard	Schallamach	Michelin	Archard	Schallamach
5.80%	5.27%	4.09%	5.59%	3.93%	2.62%
275/80 2					
Front tires			**Rear tires**		
Michelin	Archard	Schallamach	Michelin	Archard	Schallamach
7.42%	6.91%	3.89%	6.60%	6.05%	4.09%

The three models show an increase on wear when the tires are inflated over their recommended value. This was expected for Archard's model since Figure 27 and Figure 28 show a decrease on the surface area value from 7.5 bar to 8.0 bar. It is true that the hardness modulus increases, but its magnitude is inferior to the surface area magnitude. For the slip distance, it can also be seen in Figure 23 to Figure 26 that its value slightly increases when the inflation pressure is augmented, thus, Schallamach's model also indicates an increase on wear.

Table 7 presents a comparison between the two tires in terms of wear for each model and pressure.

Table 7 – Tire wear comparison

275/80 1 → 275/80 2					
Front tires					
Michelin		Archard		Schallamach	
7.5 bar	8.0 bar	7.5 bar	8.0 bar	7.5 bar	8.0 bar
-19.81%	-18.59%	12.75%	14.50%	-4.94%	-5.13%
Rear tires					
Michelin		Archard		Schallamach	
7.5 bar	8.0 bar	7.5 bar	8.0 bar	7.5 bar	8.0 bar
-25.50%	-24.79%	7.82%	10.01%	-4.50%	-3.13%

The models respond in different ways when tire 1 is replaced by tire 2. Michelin's and Schallamach's models estimate a decrease on wear. However, Archard's model shows an increase on wear.

7 CONCLUSION

All three wear models show a greater impact of the lateral force on the global tire wear over the longitudinal force for front tires. This phenomenon was expected since the lateral slip values plotted on Figure 24 and Figure 26 were higher than longitudinal slip values in Figure 23 and Figure 25. For Archard's model, another indication is the fact that the hardness modules H_y calculated in Figure 28 are greater than hardness modules H_x calculated in Figure 27. However, Michelin's model shows that, for rear tires, the longitudinal force has a greater impact on total wear than the lateral force.

The rear axle is the driving axle, so it is expected for the longitudinal forces to be greater on the rear axle than on the front axle. Another point is that, since there are four tires on the rear axle, the lateral forces will be better distributed than on the front axles. Truck model [1] results in Figure 29 and Figure 31 show this relation.

For these reasons, Michelin's result is reasonable, but it does not explain why Archard's and Schallamach's models show a different result. The reason is the influence of each parameter on the estimated wear, especially, the forces impact. The exponent value of each parameter must be better defined using empirical tests.

The models also indicate that over inflation causes an increase in tire wear compared to the wear when the tire is inflated at the recommended value. In that comparison, Archard's model has a closer response to Michelin's model than Schallamach's. However, when it comes to comparing tires, Archard's model responds differently from the other two, showing that tire 2 wears more than tire 1.

8 FUTURE WORKS

To continue this work, usage tests with 4x2 trucks could be performed in order to compare models results with real usage and, afterwards, empirically determine exponents' values to approximate Archard's model to reality, but always respecting the unit:

$$P = \frac{{F_x}^a \cdot {s_x}^b}{{H_x}^c \cdot {A_x}^d} + \frac{{F_y}^a \cdot {s_Y}^b}{{H_y}^c \cdot {A_y}^d} \tag{13}$$

By doing this, the importance of each parameter for tire wear would be better determined.

The analysis of the difference in wear between driving axle tires and non-driving axle tires could also be done. For that, it would be necessary to analyze the wear of each rib of the tread band. This would also provide developers with an idea of how irregular wear takes place.

This method could be applied as well to tires of different dimensions and/or different usage conditions.

At last, another possible future work could be the analysis of the camber influence on tire wear and rib wear.

9 BIBLIOGRAPHY

[1] COELHO SANTOS, Julia – **Análise dos esforços nos pneus de um veículo a partir de seus dados de GPS** – Polytechnic School, Federal University of Rio de Janeiro – 2019

[2] Available at: https://www.michelintruck.com/tires-and-retreads/selector/info/xfe-(wb)-(steer). Accessed: August 29 2019

[3] NGENO; MOHAMMADI - **Analysis of tyre wear using the expanded brush tyre model** – Royal Institute of Technology, Stockholm – 2015

[4] SALMINEM, Henry – **Parametrizing tyre wear using a brush tyre model** – Royal Institute of Technology, Stockholm – 2014

[5] Available at: https://www.wheels-inmotion.co.uk/forum/index.php?/topic/2415-a-matter-of-pressure/. Accessed: August 9 2019

[6] Available at: http://www.sindipesa.com.br/noticias/notsind.asp?id=30755. Accessed: August 30 2019

[7] VEEN - **An analytical approach to dynamic irregular tyre wear** – Eindhoven University of Technology, Eindhoven – 2007

[8] KATO; ADACHI – **Wear Mechanisms, chapter 7, Modern Tribology Handbook**

[9] WILLIAMS, John – **Engineering Tribology** – 2005. Available at: https://books.google.com.br/books?id=Kx1tjzBv2ZEC&printsec=frontcover#v=onepage&q&f=false. Accessed: August 27 2019

[10] H. C. Meng, K. C. Ludema – **Wear models and predictive equations: their forms and content** – 1994

APPENDIX A – Usage research form

Uso do Pneu 275/80 R22.5

Este curto questionário faz parte do projeto de alunos de Engenharia Mecânica da UFRJ. Seu propósito é de melhor compreender o uso deste pneu pelas transportadoras a fim de tornar as simulações de uso mais próximas da realidade.
Agradecemos desde já sua participação.

1. Qual o nome da sua transportadora?

____

2. Quantos caminhões tem a sua frota?

____

3. Que tipo de carga costumam transportar com mais frequência?
Marcar apenas uma oval.

- ◯ Cargas Secas
- ◯ Granel Sólido
- ◯ Granel Líquido
- ◯ Frigoríficas
- ◯ Medicamentos
- ◯ Minério e Cimento
- ◯ Cargas de Veículo
- ◯ Cargas Frágil
- ◯ Cargas de Valor
- ◯ Cargas Vivas
- ◯ Mudanças
- ◯ Encomendas
- ◯ Outro: ______________________

4. Quantos caminhões 4x2 (Toco) há na frota de sua empresa?

____

5. Peso da carga transportada por caminhões 4x2 (sem contar o peso do caminhão)
Para informação, um caminhão 4x2 (Toco), em média, pesa 10 Toneladas.
Marcar apenas uma oval por linha.

	Maior parte do tempo	Às vezes	Nunca
1 tonelada ou menos	◯	◯	◯
2 ton	◯	◯	◯
3 ton	◯	◯	◯
4 ton	◯	◯	◯
5 ton	◯	◯	◯
6 toneladas ou mais	◯	◯	◯

6. **Qual trajeto é o mais comum (Origem e destino) destes caminhões 4x2 Toco?**

____

7. **Quantos pneus costumam comprar anualmente?**

____

8. **Identifique o uso das marcas abaixo para pneus 275/80 R22.5:**
Marcar apenas uma oval por linha.

	Maior parte do uso	Boa parte do uso	Médio uso	Pouco usada	Não usada
Bridgestone	◯	◯	◯	◯	◯
Continental	◯	◯	◯	◯	◯
Goodyear	◯	◯	◯	◯	◯
Michelin	◯	◯	◯	◯	◯
Pirelli	◯	◯	◯	◯	◯
Outra	◯	◯	◯	◯	◯

9. **[Opcional] Se sua resposta na pergunta anterior foi "Outra", qual marca?**

____

10. **Que pressão costuma ser usada nos pneus 275/80?**
Marcar apenas uma oval.

◯ 102 psi / 7.0 bar
◯ 109 psi / 7.5 bar
◯ 116 psi / 8.0 bar
◯ 123 psi / 8.5 bar
◯ 131 psi / 9.0 bar
◯ Outro: _______________________________________

11. **Qual é, em média, a quilometragem de desmonte até a substituição do pneu?**
Quilometragem de vida útil sem considerar recapagem (1ª Vida)
Marcar apenas uma oval.

◯ Abaixo de 40.000 Km
◯ 40.000 a 80.000 Km
◯ 80.000 a 120.000 Km
◯ 120.000 a 160.000 Km
◯ 160.000 a 200.000 Km
◯ 200.000 a 240.000 Km
◯ Acima de 240.000 Km

12. **Qual a profundidade de escultura no momento do desmonte (substituição do pneu)?**
Profundidade do piso do pneu / Profundidade do sulco / Profundidade do perfil
Marcar apenas uma oval.

- Abaixo de 1,6 mm
- 1,6 a 3,0 mm
- 3,0 a 4,0 mm
- 4,0 a 5,0 mm
- 5,0 a 6,0 mm
- Acima de 6,0 mm

13. **Relacione as causas de desmonte de pneu 275/80 com suas frequências**
Marcar apenas uma oval por linha.

	Muita ocorrência	Boa ocorrência	Média ocorrência	Pouca ocorrência	N/A
Fim de vida útil					
Acidente com o veículo					
Problemas de conforto					
Furo no pneu					
Bolha no pneu					
Pneu estourou					
Desgaste irregular					
Pneu rasgou					

14. **Estaria disponível para entrarmos em contato e coletarmos mais informações sobre o uso? Se sim, informe um telefone para contato ou e-mail.**

APPENDIX B – Table of wear coefficient, *k*, for different metals

Material	K
Mild steel (on mild steel)	7×10^{-3}
α/β brass	6×10^{-4}
PTFE	2.5×10^{-5}
Copper-beryllium	3.7×10^{-5}
Hard tool steel	1.3×10^{-4}
Ferritic stainless steel	1.7×10^{-5}
Polythene	1.3×10^{-7}
PMMA	7×10^{-6}

APPENDIX C – MATLAB codes

```
% Tire wear model part 1

% Commentaries:
% Code to select the appropriate parameters given the
vehicle model outputs
% Before running the model, the vehicle outputs and the
database must be
% formatted according to the model used before. It is
important to maintain
% the parameters at the right positions!!!
% The forces at the vehicle model outputs is in Newton and
the forces at
% the FEM database is in daN

clear; clc;

load('C:\Users\-----\Documents\MATLAB\raw_forces.mat');
% Vehicle model outputs
load('C:\Users\-----\Documents\MATLAB\tire_database.mat');
% FEM database

sz = size(Base_data); % Time / Km / Speed
%____________________________________________________________
_________________
%
H1x = 0; H2x = 0; % Hardness modulus tire 1 / tire 2
[N/mm2]
S1x = 0; S2x = 0; % Surface area tire 1 / tire 2 [mm2]
h1x = 0; h2x = 0; % Tread band height tire 1 / tire 2 [mm]
L1x = 0; L2x = 0; % Surface area medium lenght tire 1 /
tire 2 [mm]
s1x = 0; s2x = 0; % Slip distance tire 1 / tire 2 [mm]

F = AVG_raw; % To analyze another tire position, change to
AVG/AVD/ARGE/ARGI/ARDI/ARDE

for i = 1:sz(1,1)% Interpolations for longitudinal wear
    if F(i,3) <= 10000
        % Tire 1
        H1x(i,1) = P275_1_75(12,1); S1x(i,1) =
P275_1_75(12,2);
        h1x(i,1) = P275_1_75(13,1); L1x(i,1) =
P275_1_75(13,2);
        H1x(i,2) = P275_1_80(12,1); S1x(i,2) =
P275_1_80(12,2);
        h1x(i,2) = P275_1_80(13,1); L1x(i,2) =
P275_1_80(13,2);
        % Tire 2
```

```
        H2x(i,1) = P275_2_75(12,1); S2x(i,1) =
P275_2_75(12,2);
        h2x(i,1) = P275_2_75(13,1); L2x(i,1) =
P275_2_75(13,2);
        H2x(i,2) = P275_2_80(12,1); S2x(i,2) =
P275_2_80(12,2);
        h2x(i,2) = P275_2_80(13,1); L2x(i,2) =
P275_2_80(13,2);

        if F(i,1) <= -3000
            % Tire 1
            s1x(i,1) = P275_1_75(3,2); s1x(i,2) =
P275_1_80(3,2);
            % Tire 2
            s2x(i,1) = P275_2_75(3,2); s2x(i,2) =
P275_2_80(3,2);
        end

        for n = 3:9
            if F(i,1) > P275_1_75(n,1)*10 && F(i,1) <=
P275_1_75(n+1,1)*10
                % Tire 1
                s1x(i,1)=((F(i,1)-
P275_1_75(n,1)*10)/1000)*(P275_1_75(n+1,2)-
P275_1_75(n,2))+P275_1_75(n,2);
                s1x(i,2)=((F(i,1)-
P275_1_80(n,1)*10)/1000)*(P275_1_80(n+1,2)-
P275_1_80(n,2))+P275_1_80(n,2);
                % Tire 2
                s2x(i,1)=((F(i,1)-
P275_2_75(n,1)*10)/1000)*(P275_2_75(n+1,2)-
P275_2_75(n,2))+P275_2_75(n,2);
                s2x(i,2)=((F(i,1)-
P275_2_80(n,1)*10)/1000)*(P275_2_80(n+1,2)-
P275_2_80(n,2))+P275_2_80(n,2);
            end
        end

        if F(i,1) > 4000
            % Tire 1
            s1x(i,1) = P275_1_75(10,2); s1x(i,2) =
P275_1_80(10,2);
            % Tire 2
            s2x(i,1) = P275_2_75(10,2); s2x(i,2) =
P275_2_80(10,2);
        end
    end

    for m = [1,4,7,10,13]
        if F(i,3) > P275_1_75(1,m)*10 && F(i,3) <=
P275_1_75(1,m+3)*10
```

```
            % Tire 1
            H1x(i,1)=((F(i,3)-
P275_1_75(1,m)*10)/5000)*(P275_1_75(12,m+3)-
P275_1_75(12,m))+P275_1_75(12,m);
            S1x(i,1)=((F(i,3)-
P275_1_75(1,m)*10)/5000)*(P275_1_75(12,m+4)-
P275_1_75(12,m+1))+P275_1_75(12,m+1);
            h1x(i,1)=((F(i,3)-
P275_1_75(1,m)*10)/5000)*(P275_1_75(13,m+3)-
P275_1_75(13,m))+P275_1_75(13,m);
            L1x(i,1)=((F(i,3)-
P275_1_75(1,m)*10)/5000)*(P275_1_75(13,m+4)-
P275_1_75(13,m+1))+P275_1_75(13,m+1);
            H1x(i,2)=((F(i,3)-
P275_1_80(1,m)*10)/5000)*(P275_1_80(12,m+3)-
P275_1_80(12,m))+P275_1_80(12,m);
            S1x(i,2)=((F(i,3)-
P275_1_80(1,m)*10)/5000)*(P275_1_80(12,m+4)-
P275_1_80(12,m+1))+P275_1_80(12,m+1);
            h1x(i,2)=((F(i,3)-
P275_1_80(1,m)*10)/5000)*(P275_1_80(13,m+3)-
P275_1_80(13,m))+P275_1_80(13,m);
            L1x(i,2)=((F(i,3)-
P275_1_80(1,m)*10)/5000)*(P275_1_80(13,m+4)-
P275_1_80(13,m+1))+P275_1_80(13,m+1);
            % Tire 2
            H2x(i,1)=((F(i,3)-
P275_2_75(1,m)*10)/5000)*(P275_2_75(12,m+3)-
P275_2_75(12,m))+P275_2_75(12,m);
            S2x(i,1)=((F(i,3)-
P275_2_75(1,m)*10)/5000)*(P275_2_75(12,m+4)-
P275_2_75(12,m+1))+P275_2_75(12,m+1);
            h2x(i,1)=((F(i,3)-
P275_2_75(1,m)*10)/5000)*(P275_2_75(13,m+3)-
P275_2_75(13,m))+P275_2_75(13,m);
            L2x(i,1)=((F(i,3)-
P275_2_75(1,m)*10)/5000)*(P275_2_75(13,m+4)-
P275_2_75(13,m+1))+P275_2_75(13,m+1);
            H2x(i,2)=((F(i,3)-
P275_2_80(1,m)*10)/5000)*(P275_2_80(12,m+3)-
P275_2_80(12,m))+P275_2_80(12,m);
            S2x(i,2)=((F(i,3)-
P275_2_80(1,m)*10)/5000)*(P275_2_80(12,m+4)-
P275_2_80(12,m+1))+P275_2_80(12,m+1);
            h2x(i,2)=((F(i,3)-
P275_2_80(1,m)*10)/5000)*(P275_2_80(13,m+3)-
P275_2_80(13,m))+P275_2_80(13,m);
            L2x(i,2)=((F(i,3)-
P275_2_80(1,m)*10)/5000)*(P275_2_80(13,m+4)-
P275_2_80(13,m+1))+P275_2_80(13,m+1);
```

```
            if F(i,1) <= -3000
                % Tire 1
                s1x(i,1) = P275_1_75(3,m+1); s1x(i,2) =
P275_1_80(3,m+1);
                % Tire 2
                s2x(i,1) = P275_2_75(3,m+1); s2x(i,2) =
P275_2_80(3,m+1);
            end

            for n = 3:9
                if F(i,1) > P275_1_75(n,m)*10 && F(i,1) <=
P275_1_75(n+1,m)*10
                    % Tire 1
                    s1x(i,1)=((F(i,1)-
P275_1_75(n,m)*10)/1000)*(P275_1_75(n+1,m+1)-
P275_1_75(n,m+1))+P275_1_75(n,m+1);
                    s1x(i,2)=((F(i,1)-
P275_1_80(n,m)*10)/1000)*(P275_1_80(n+1,m+1)-
P275_1_80(n,m+1))+P275_1_80(n,m+1);
                    % Tire 2
                    s2x(i,1)=((F(i,1)-
P275_2_75(n,m)*10)/1000)*(P275_2_75(n+1,m+1)-
P275_2_75(n,m+1))+P275_2_75(n,m+1);
                    s2x(i,2)=((F(i,1)-
P275_2_80(n,m)*10)/1000)*(P275_2_80(n+1,m+1)-
P275_2_80(n,m+1))+P275_2_80(n,m+1);
                end
            end

            if F(i,1) > 4000
                % Tire 1
                s1x(i,1) = P275_1_75(10,m+1); s1x(i,2) =
P275_1_80(10,m+1);
                % Tire 2
                s2x(i,1) = P275_2_75(10,m+1); s2x(i,2) =
P275_2_80(10,m+1);
            end
        end
    end

    if F(i,3) >= 35000
        % Tire 1
        H1x(i,1) = P275_1_75(12,16); S1x(i,1) =
P275_1_75(12,17);
        h1x(i,1) = P275_1_75(13,16); L1x(i,1) =
P275_1_75(13,17);
        H1x(i,2) = P275_1_80(12,16); S1x(i,2) =
P275_1_80(12,17);
        h1x(i,2) = P275_1_80(13,16); L1x(i,2) =
P275_1_80(13,17);
        % Tire 2
```

```
        H2x(i,1) = P275_2_75(12,16); S2x(i,1) =
P275_2_75(12,17);
        h2x(i,1) = P275_2_75(13,16); L2x(i,1) =
P275_2_75(13,17);
        H2x(i,2) = P275_2_80(12,16); S2x(i,2) =
P275_2_80(12,17);
        h2x(i,2) = P275_2_80(13,16); L2x(i,2) =
P275_2_80(13,17);

        if F(i,1) <= -3000
            % Tire 1
            s1x(i,1) = P275_1_75(3,17); s1x(i,2) =
P275_1_80(3,17);
            % Tire 2
            s2x(i,1) = P275_2_75(3,17); s2x(i,2) =
P275_2_80(3,17);
        end

        for n = 3:9
            if F(i,1) > P275_1_75(n,1)*10 && F(i,1) <=
P275_1_75(n+1,1)*10
                % Tire 1
                s1x(i,1)=((F(i,1)-
P275_1_75(n,16)*10)/1000)*(P275_1_75(n+1,17)-
P275_1_75(n,17))+P275_1_75(n,17);
                s1x(i,2)=((F(i,1)-
P275_1_80(n,16)*10)/1000)*(P275_1_80(n+1,17)-
P275_1_80(n,17))+P275_1_80(n,17);
                % Tire 2
                s2x(i,1)=((F(i,1)-
P275_2_75(n,16)*10)/1000)*(P275_2_75(n+1,17)-
P275_2_75(n,17))+P275_2_75(n,17);
                s2x(i,2)=((F(i,1)-
P275_2_80(n,16)*10)/1000)*(P275_2_80(n+1,17)-
P275_2_80(n,17))+P275_2_80(n,17);
            end
        end

        if F(i,1) > 4000
            % Tire 1
            s1x(i,1) = P275_1_75(10,17); s1x(i,2) =
P275_1_80(10,17);
            % Tire 2
            s2x(i,1) = P275_2_75(10,17); s2x(i,2) =
P275_2_80(10,17);
        end
    end
end
%___________________________________________________________
________________
%
```

```
H1y = 0; H2y = 0; % Hardness modulus [N/mm2]
S1y = 0; S2y = 0; % Surface area [mm2]
h1y = 0; h2y = 0; % Tread band height [mm]
L1y = 0; L2y = 0; % Surface area medium lenght [mm]
s1y = 0; s2y = 0; % Slip distance [mm]

for i = 1:sz(1,1) % Interpolations for lateral wear
    if F(i,3) <= 10000
        % Tire 1
        H1y(i,1) = P275_1_75(30,1); S1y(i,1) =
P275_1_75(30,2);
        h1y(i,1) = P275_1_75(31,1); L1y(i,1) =
P275_1_75(31,2);
        H1y(i,2) = P275_1_80(30,1); S1y(i,2) =
P275_1_80(30,2);
        h1y(i,2) = P275_1_80(31,1); L1y(i,2) =
P275_1_80(31,2);
        % Tire 2
        H2y(i,1) = P275_2_75(30,1); S2y(i,1) =
P275_2_75(30,2);
        h2y(i,1) = P275_2_75(31,1); L2y(i,1) =
P275_2_75(31,2);
        H2y(i,2) = P275_2_80(30,1); S2y(i,2) =
P275_2_80(30,2);
        h2y(i,2) = P275_2_80(31,1); L2y(i,2) =
P275_2_80(31,2);

        if F(i,2) <= -5000
            % Tire 1
            s1y(i,1) = P275_1_75(18,2); s1y(i,2) =
P275_1_80(18,2);
            % Tire 2
            s2y(i,1) = P275_2_75(18,2); s2y(i,2) =
P275_2_80(18,2);
        end

        for n = 18:27
            if F(i,2) > P275_1_75(n,1)*10 && F(i,2) <=
P275_1_75(n+1,1)*10
                % Tire 1
                s1y(i,1)=((F(i,2)-
P275_1_75(n,1)*10)/1000)*(P275_1_75(n+1,2)-
P275_1_75(n,2))+P275_1_75(n,2);
                s1y(i,2)=((F(i,2)-
P275_1_80(n,1)*10)/1000)*(P275_1_80(n+1,2)-
P275_1_80(n,2))+P275_1_80(n,2);
                % Tire 2
                s2y(i,1)=((F(i,2)-
P275_2_75(n,1)*10)/1000)*(P275_2_75(n+1,2)-
P275_2_75(n,2))+P275_2_75(n,2);
```

```
                s2y(i,2)=((F(i,2)-
P275_2_80(n,1)*10)/1000)*(P275_2_80(n+1,2)-
P275_2_80(n,2))+P275_2_80(n,2);
            end
        end

        if F(i,2) > 5000
            % Tire 1
            s1y(i,1) = P275_1_75(28,2); s1y(i,2) =
P275_1_80(28,2);
            % Tire 2
            s2y(i,1) = P275_2_75(28,2); s2y(i,2) =
P275_2_80(28,2);
        end
    end

    for m = [1,4,7,10,13]
        if F(i,3) > P275_1_75(1,m)*10 && F(i,3) <=
P275_1_75(1,m+3)*10
            % Tire 1
            H1y(i,1)=((F(i,3)-
P275_1_75(1,m)*10)/5000)*(P275_1_75(30,m+3)-
P275_1_75(30,m))+P275_1_75(30,m);
            S1y(i,1)=((F(i,3)-
P275_1_75(1,m)*10)/5000)*(P275_1_75(30,m+4)-
P275_1_75(30,m+1))+P275_1_75(30,m+1);
            h1y(i,1)=((F(i,3)-
P275_1_75(1,m)*10)/5000)*(P275_1_75(31,m+3)-
P275_1_75(31,m))+P275_1_75(31,m);
            L1y(i,1)=((F(i,3)-
P275_1_75(1,m)*10)/5000)*(P275_1_75(31,m+4)-
P275_1_75(31,m+1))+P275_1_75(31,m+1);
            H1y(i,2)=((F(i,3)-
P275_1_80(1,m)*10)/5000)*(P275_1_80(30,m+3)-
P275_1_80(30,m))+P275_1_80(30,m);
            S1y(i,2)=((F(i,3)-
P275_1_80(1,m)*10)/5000)*(P275_1_80(30,m+4)-
P275_1_80(30,m+1))+P275_1_80(30,m+1);
            h1y(i,2)=((F(i,3)-
P275_1_80(1,m)*10)/5000)*(P275_1_80(31,m+3)-
P275_1_80(31,m))+P275_1_80(31,m);
            L1y(i,2)=((F(i,3)-
P275_1_80(1,m)*10)/5000)*(P275_1_80(31,m+4)-
P275_1_80(31,m+1))+P275_1_80(31,m+1);
            % Tire 2
            H2y(i,1)=((F(i,3)-
P275_2_75(1,m)*10)/5000)*(P275_2_75(30,m+3)-
P275_2_75(30,m))+P275_2_75(30,m);
            S2y(i,1)=((F(i,3)-
P275_2_75(1,m)*10)/5000)*(P275_2_75(30,m+4)-
P275_2_75(30,m+1))+P275_2_75(30,m+1);
```

```
            h2y(i,1)=((F(i,3)-
P275_2_75(1,m)*10)/5000)*(P275_2_75(31,m+3)-
P275_2_75(31,m))+P275_2_75(31,m);
            L2y(i,1)=((F(i,3)-
P275_2_75(1,m)*10)/5000)*(P275_2_75(31,m+4)-
P275_2_75(31,m+1))+P275_2_75(31,m+1);
            H2y(i,2)=((F(i,3)-
P275_2_80(1,m)*10)/5000)*(P275_2_80(30,m+3)-
P275_2_80(30,m))+P275_2_80(30,m);
            S2y(i,2)=((F(i,3)-
P275_2_80(1,m)*10)/5000)*(P275_2_80(30,m+4)-
P275_2_80(30,m+1))+P275_2_80(30,m+1);
            h2y(i,2)=((F(i,3)-
P275_2_80(1,m)*10)/5000)*(P275_2_80(31,m+3)-
P275_2_80(31,m))+P275_2_80(31,m);
            L2y(i,2)=((F(i,3)-
P275_2_80(1,m)*10)/5000)*(P275_2_80(31,m+4)-
P275_2_80(31,m+1))+P275_2_80(31,m+1);

            if F(i,2) <= -5000
                % Tire 1
                s1y(i,1) = P275_1_75(18,m+1); s1y(i,2) =
P275_1_80(18,m+1);
                % Tire 2
                s2y(i,1) = P275_2_75(18,m+1); s2y(i,2) =
P275_2_80(18,m+1);
            end

            for n = 18:27
                if F(i,2) > P275_1_75(n,m)*10 && F(i,2) <=
P275_1_75(n+1,m)*10
                    % Tire 1
                    s1y(i,1)=((F(i,2)-
P275_1_75(n,m)*10)/1000)*(P275_1_75(n+1,m+1)-
P275_1_75(n,m+1))+P275_1_75(n,m+1);
                    s1y(i,2)=((F(i,2)-
P275_1_80(n,m)*10)/1000)*(P275_1_80(n+1,m+1)-
P275_1_80(n,m+1))+P275_1_80(n,m+1);
                    % Tire 2
                    s2y(i,1)=((F(i,2)-
P275_2_75(n,m)*10)/1000)*(P275_2_75(n+1,m+1)-
P275_2_75(n,m+1))+P275_2_75(n,m+1);
                    s2y(i,2)=((F(i,2)-
P275_2_80(n,m)*10)/1000)*(P275_2_80(n+1,m+1)-
P275_2_80(n,m+1))+P275_2_80(n,m+1);
                end
            end

            if F(i,2) > 5000
                % Tire 1
```

```
                s1y(i,1) = P275_1_75(28,m+1); s1y(i,2) =
P275_1_80(28,m+1);
                % Tire 2
                s2y(i,1) = P275_2_75(28,m+1); s2y(i,2) =
P275_2_80(28,m+1);
            end
        end
    end

    if F(i,3) >= 35000
        % Tire 1
        H1y(i,1) = P275_1_75(30,16); S1y(i,1) =
P275_1_75(30,17);
        h1y(i,1) = P275_1_75(31,16); L1y(i,1) =
P275_1_75(31,17);
        H1y(i,2) = P275_1_80(30,16); S1y(i,2) =
P275_1_80(30,17);
        h1y(i,2) = P275_1_80(31,16); L1y(i,2) =
P275_1_80(31,17);
        % Tire 2
        H2y(i,1) = P275_2_75(30,16); S2y(i,1) =
P275_2_75(30,17);
        h2y(i,1) = P275_2_75(31,16); L2y(i,1) =
P275_2_75(31,17);
        H2y(i,2) = P275_2_80(30,16); S2y(i,2) =
P275_2_80(30,17);
        h2y(i,2) = P275_2_80(31,16); L2y(i,2) =
P275_2_80(31,17);

        if F(i,2) <= -5000
            % Tire 1
            s1y(i,1) = P275_1_75(18,17); s1y(i,2) =
P275_1_80(18,17);
            % Tire 2
            s2y(i,1) = P275_2_75(18,17); s2y(i,2) =
P275_2_80(18,17);
        end

        for n = 18:27
            if F(i,2) > P275_1_75(n,1)*10 && F(i,2) <=
P275_1_75(n+1,1)*10
                % Tire 1
                s1y(i,1)=((F(i,2)-
P275_1_75(n,16)*10)/1000)*(P275_1_75(n+1,17)-
P275_1_75(n,17))+P275_1_75(n,17);
                s1y(i,2)=((F(i,2)-
P275_1_80(n,16)*10)/1000)*(P275_1_80(n+1,17)-
P275_1_80(n,17))+P275_1_80(n,17);
                % Tire 2
```

```
                s2y(i,1)=((F(i,2)-
P275_2_75(n,16)*10)/1000)*(P275_2_75(n+1,17)-
P275_2_75(n,17))+P275_2_75(n,17);
                s2y(i,2)=((F(i,2)-
P275_2_80(n,16)*10)/1000)*(P275_2_80(n+1,17)-
P275_2_80(n,17))+P275_2_80(n,17);
            end
        end

        if F(i,2) > 5000
            % Tire 1
            s1y(i,1) = P275_1_75(28,17); s1y(i,2) =
P275_1_80(28,17);
            % Tire 2
            s2y(i,1) = P275_2_75(28,17); s2y(i,2) =
P275_2_80(28,17);
        end
    end
end
```

```
% Tire wear model part 2

P1AVG_wear = 0; P2AVG_wear = 0; BD = Base_data;

F = abs(F); s1x = abs(s1x); s1y = abs(s1y); s2x = abs(s2x);
s2y = abs(s2y);

for i = 2:sz(1,1)
    % Michelin


%% CONFIDENTIAL


    % Archard
    P1AVG_wear(i,9)  = F(i,1)*(s1x(i,1)*(BD(i,2)-BD(i-
1,2))/L1x(i,1))/(H1x(i,1)*S1x(i,1)); % X wear for 7.5 bar
    P1AVG_wear(i,10) = F(i,2)*(s1y(i,1)*(BD(i,2)-BD(i-
1,2))/L1y(i,1))/(H1y(i,1)*S1y(i,1)); % Y wear for 7.5 bar
    P1AVG_wear(i,11) = P1AVG_wear(i,9) + P1AVG_wear(i,10);
% Total wear for 7.5 bar

    P1AVG_wear(i,13) = F(i,1)*(s1x(i,2)*(BD(i,2)-BD(i-
1,2))/L1x(i,2))/(H1x(i,2)*S1x(i,2)); % X wear for 8.0 bar
    P1AVG_wear(i,14) = F(i,2)*(s1y(i,2)*(BD(i,2)-BD(i-
1,2))/L1y(i,2))/(H1y(i,2)*S1y(i,2)); % Y wear for 8.0 bar
    P1AVG_wear(i,15) = P1AVG_wear(i,13) + P1AVG_wear(i,14);
% Total wear for 8.0 bar

    P2AVG_wear(i,9)  = F(i,1)*(s2x(i,1)*(BD(i,2)-BD(i-
1,2))/L2x(i,1))/(H2x(i,1)*S2x(i,1)); % X wear for 7.5 bar
    P2AVG_wear(i,10) = F(i,2)*(s2y(i,1)*(BD(i,2)-BD(i-
1,2))/L2y(i,1))/(H2y(i,1)*S2y(i,1)); % Y wear for 7.5 bar
    P2AVG_wear(i,11) = P2AVG_wear(i,9) + P2AVG_wear(i,10);
% Total wear for 7.5 bar

    P2AVG_wear(i,13) = F(i,1)*(s2x(i,2)*(BD(i,2)-BD(i-
1,2))/L2x(i,2))/(H2x(i,2)*S2x(i,2)); % X wear for 8.0 bar
    P2AVG_wear(i,14) = F(i,2)*(s2y(i,2)*(BD(i,2)-BD(i-
1,2))/L2y(i,2))/(H2y(i,2)*S2y(i,2)); % Y wear for 8.0 bar
    P2AVG_wear(i,15) = P2AVG_wear(i,13) + P2AVG_wear(i,14);
% Total wear for 8.0 bar

    % Schallamach
    P1AVG_wear(i,17) = F(i,1)*s1x(i,1)*(BD(i,2)-BD(i-
1,2))/L1x(i,1); % X wear for 7.5 bar
    P1AVG_wear(i,18) = F(i,2)*s1y(i,1)*(BD(i,2)-BD(i-
1,2))/L1y(i,1); % Y wear for 7.5 bar
    P1AVG_wear(i,19) = P1AVG_wear(i,17) + P1AVG_wear(i,18);
% Total wear for 7.5 bar
```

```
    P1AVG_wear(i,21) = F(i,1)*s1x(i,2)*(BD(i,2)-BD(i-
1,2))/L1x(i,2); % X wear for 8.0 bar
    P1AVG_wear(i,22) = F(i,2)*s1y(i,2)*(BD(i,2)-BD(i-
1,2))/L1y(i,2); % Y wear for 8.0 bar
    P1AVG_wear(i,23) = P1AVG_wear(i,21) + P1AVG_wear(i,22);
% Total wear for 8.0 bar

    P2AVG_wear(i,17) = F(i,1)*s2x(i,1)*(BD(i,2)-BD(i-
1,2))/L2x(i,1); % X wear for 7.5 bar
    P2AVG_wear(i,18) = F(i,2)*s2y(i,1)*(BD(i,2)-BD(i-
1,2))/L2y(i,1); % Y wear for 7.5 bar
    P2AVG_wear(i,19) = P2AVG_wear(i,17) + P2AVG_wear(i,18);
% Total wear for 7.5 bar

    P2AVG_wear(i,21) = F(i,1)*s2x(i,2)*(BD(i,2)-BD(i-
1,2))/L2x(i,2); % X wear for 8.0 bar
    P2AVG_wear(i,22) = F(i,2)*s2y(i,2)*(BD(i,2)-BD(i-
1,2))/L2y(i,2); % Y wear for 8.0 bar
    P2AVG_wear(i,23) = P2AVG_wear(i,21) + P2AVG_wear(i,22);
% Total wear for 8.0 bar
end

P1AVG_wear(sz(1,1)+1,23) = 0; P2AVG_wear(sz(1,1)+1,23) = 0;

for i = 1:23
    for n = 1:sz(1,1)
        P1AVG_wear(sz(1,1)+1,i) = P1AVG_wear(sz(1,1)+1,i) +
P1AVG_wear(n,i);
        P2AVG_wear(sz(1,1)+1,i) = P2AVG_wear(sz(1,1)+1,i) +
P2AVG_wear(n,i);
    end
end
```