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STUDY ON THE TIRE TREAD WEAR ESTIMATION

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Abstract. *Nowadays, with the advancement of technology and the search for new high quality products there is also an increase in specifications and tolerances leading to an increase in validation tests with a shorter time. Therefore, this project aims to propose a model to reduce the mileage, time and cost of the tire tests. For this purpose, a new mathematical model was developed at MATLAB® to calculate and estimate the tire tread lifespan at a shorter time. The results show a significant test time and cost reduction with the adequacy of the models of least squares and maximum likelihood.*

Keywords: *tire, tread wear, TWI, Maximum Likelihood and Least Squares.*

1. INTRODUCTION

The tire is a complex product, built with different types of components that utilize a large variety of raw materials. Tires are the only point of contact between the vehicle and road, therefore, that it is the most fundamental component to passenger's and driver's safety (Pacjeka, 2012). Besides, tires perform other essential functions to ensure vehicle's drivability, safety and good performance. On top of that, the tire needs to be durable and have a long service life. Nowadays, one of the market requirements is the proof of the durability of a tire or tire service life, therefore, tire manufacturers are investing time and money to ensure that their new products undergo durability and service life tests. In current models, the companies that conduct tire durability tests use a linear mathematical model to estimate the tire service life. However, in order to achieve this goal, it is necessary to run the tires until their tread wear indicator (TWI) has been reached, in which case it may take a mileage of 40,000 km or higher. Intermediary measurements of the tread wear is done every 5,000 km to be used in the mathematical model to estimate the tire life. This kind of test can take at least nine weeks and has a high cost. Because of that this paper aims to estimate tire service life with the use of nonlinear mathematical models such as Least Squares and Maximum Likelihood, with the purpose of achieving a higher reliability of the results obtained, due to the fact that rubber shows a nonlinear behavior and thus, ensuring cost reduction in fuel consumption and human resources (Ruggiero, 2000).

2. TIRE COMPONENTS

The rubber compound varies in tires. Elastomers are chemicals classified as a polymer. Polymers consist of a large amount of carbon and hydrogen molecules bonded together. These molecules are joined into a molecular chain of several repeating structural units known as monomers as shown in Fig.1, hence the name polymer (in Greek: *Poly* = "many" and *mer* = "parts") (Gent, 2012).

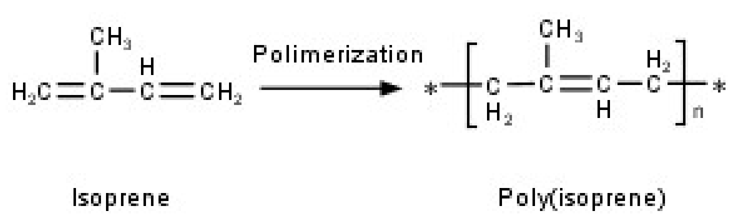

Figure 1. Chemical reaction to produce Poly(isoprene) (Natural Rubber).

The tread composition is a mix of synthetic elastomers, which are basically SBR (Styrene-Butadiene Rubber) and BR (Butyl Rubber), as well as natural rubber and fillers. The function of these elastomers is to enhance durability of the tread and increase its grip (Dick, 2001).

Development of a new product takes at least 5 years according to Jung and Cho (2006), many hours of engineering, and thousands of kilometers run for evaluation tests, meant to verify the predetermined aspects and performance intended by manufacturers. In basic terms, tires are composed of the inner liner, radial ply, tread, bead, apex and sidewall, onto which all the tire information is molded.

The tread is the part of a tire which touches the road and consists of a layer of rubber in which several grooves are designed to form a tread pattern. The front of the tire pattern has the function of draining the water to the sides of the tire, the central area of the pattern functions as a dryer of the road, and the rear area of the pattern expels the residual water remained on the road. The tire tread has others significant functions. It provides the grip on the road, tire tread lifespan, wear and aggressions resistance, low rolling resistances and acoustic comfort on a smooth surface. It also participates in steering and contributes to esthetics, which is an important factor for many customers.

3. TIRE MEASUREMENT

Some procedures are needed and standardized to characterize the tire dimensions for experimental tests. The measuring points are located laterally along the tread in each of the circumferential grooves and an additional point on each shoulder in a total depth slot approximately in the middle of the shoulder line as shown in Fig. 2. The tire measurement is performed every 90 degrees of the tire, circumferential locations as presented also in Fig. 2.

The equipment used for tire tread depth measurements was a digital tire tread depth gauge with a measure range from 0 to 30 mm (0 to 1.2 inches), a resolution of 0.01mm (0.0005 inches), an accuracy of ±0.03 mm and a measuring speed of <1.5 m/s.

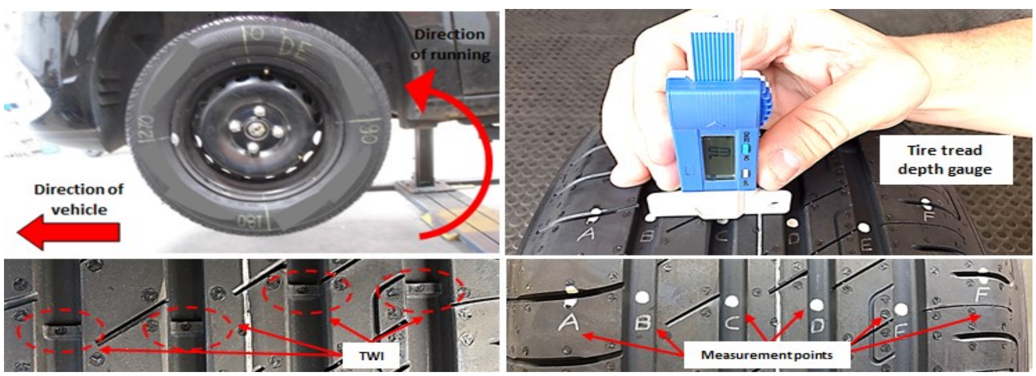

Figure 2. The circumferential locations of measurements of the tire tread wear and TWI (Tread Wear Indicator).

4. TREAD WEAR DEFINITION

Normally, some steps should be followed to calculate wear and tire lifespan, according to the test procedure of a specialized company (TWTESTES, 2017):

The first step is to measure the depth of the grooves of a new tire (0 km). As presented in Fig. 2, it was collected six measuring points located laterally along with the tread. For this example, these six points measured (A, B, C, D, E, F) have 6,6 mm of average groove depth. The second step is to measure the tire wear after 5000 km traveled, the average groove depth was 6,0 mm as presented in Tab. 1. Normally by standard, the tread wear indicator (TWI) is 1,6 mm (INMETRO, 2008). The third step is to conduct measurements each 5000 km until reaching the TWI to validate. However, with these two first measurements obtained, an estimation of the total mileages can be calculated with a linear approximation. Therefore, based on the tire wear, the mileage is defined as in the example presented in Tab. 1. In this case, the average wear groove is around 0,6 mm, thus to reach the TWI (wear of 5mm), the vehicle can go through around of 41666km.

Table 1. Example of linear approximation for Right Front Tire.

Mileages [km]	Groove [mm]	Wear [mm]
0	6,6	-
5000	6,0	0,6
Estimated Mileages		
41666	1,6 (TWI)	6,6-1,6 (TWI) = **5,0**

5. PROPOSAL OF TREAD WEAR CALCULATION METHODOLOGY

The proposed model of this paper aims to improve tread wear tests and to use a suitable model to calculate tire service life. The tire is considered a nonlinear model due of the nonlinear material, such as rubber. Following this characteristic, the estimation of the tread wear test should also consider and study of nonlinear models, (Pacjeka, 2012).

Therefore, the objective of the proposal is to minimize the error in the calculations of the lifespan and decrease the mileages in the tests, to make an optimization of the tests, bringing benefits to the applicant, such as reduction of costs and running time (less mileage, less fuel spent, shorter running time, greater accuracy and reliability of results).

For validation of the mathematical models, there was performed a comparison between the results provided by specialized companies and the proposed model presented. After the 30000 km travelled, the depth of the tire grooves is known through the measurements as in figure 2. In the case of the reference tire mounted in position right front (RF), it has the average depth of the tire grooves of 3.2 mm at the end of the tests. With the height of the TWI of 3.2 mm known, the first depth measurement was used when the tire was new and the second when the tire reached the mileage of 25000 km, then the calculation of the projection was performed, and it was obtained the result of 27790 km for 3.2mm. However, the projection should be 30000 km as the tests performed. This difference in mileage is the intrinsic error in the mathematical model used by specialized companies, which is not recommended model in literature (Ruggiero, 2000). The error found was 2210 km in extrapolation model used by specialized companies, the results were very precise in least squares, as shown in Fig. 3.

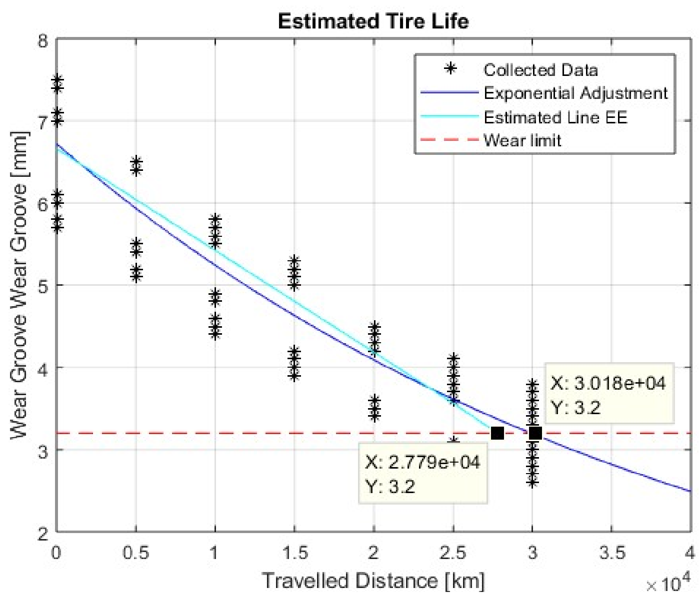

Figure 3. Comparison between Linear Extrapolation and Least Squares.

5.1 Experimental Methodology

The durability tests were performed in an outdoor environment of the Proving Grounds, on a controlled route which is 100% open roads. The driver drove all the mileage of the route and all the distance requested by the test requester as a normal driver, who makes use of his vehicle in a simple way. No load was added to the vehicle, only the driver's weight is considered in the vehicle's weight during the tests.

The route should be determined by the test requester, and should be an open course, such as: highways or urban cycles. Tire supplier or car manufacturer can use any kind, provided it satisfies the requirements of the applicant such as 20% ~ 30% city - 70% ~ 80% road, 100% city or 100% road.

In order to get the best tire wear extrapolation, it is necessary to run at least two vehicles in parallel in order to capture any changes on public highways for better comparison data, the way it was done with the control tire.

The tread wear test includes three ballast conditions for passenger cars or as requested. In the first condition the test is performed only with the driver, in the second with the driver and one passenger, and in the third with the driver and two passengers and approximately 70 kg in the trunk.

For this test two sets of tires were used: a 185 / 65R15 used as reference and mounted on vehicle 1 and the proposed tire, a 195 / 55R16 mounted on vehicle 2. For this test, the reference tire was a 185 / 65R15, mounted on vehicle 1, while the proposed tire was of a different size, a 195 / 55R16 mounted on vehicle 2. It is very common to use a control tire with technical specifications or tire size different from the proposed tire. The tire pressure used in the reference and proposed tires was 30 psi at the front and 29 psi at the rear. The tire pressure is the inflation recommended by the vehicle manufacturer.

The vehicles used in the tests have as optional different sizes of tires and wheels. Thus, for greater reliability of the results of the experiments performed in the field, the wheels used in the tests were the original wheels of the vehicles. The variation of wheel width influences the tire's footprint on the ground, as the footprint can be changed, and the final results can be modified.

The tires were held in place on the vehicles throughout the test, i.e. the tires were not rotated, nor their position was changed to ensure the most critical wear test results. In order to increase tire life, all tire manufacturers recommend front and rear caster rotation every 5000 km, as tires on the drive axle suffer from increased tread wear because of the stresses motor torque and during the braking for the front axle. In this case, the minimum tire run for test certification must be 30000 km, which represents 75% of the distance requested by applicant.

The external factors, such as the ambient and ground temperatures, the weather and the road conditions were not controlled, with the test running normally, as a regular customer traveling on a highway or through the city. However, the weather conditions should be noted in the daily reports.

The tires were visually inspected and calibrated as per the test driver daily. The calibration was always done before any running, that is, always with the cold tires, as recommended by the tire manufacturers.

The geometry of the vehicles was adjusted to the nominal value dimensions specified in the engineering drawings or to the limit tolerance values recommended by the car manufacturer in order to determine possible production tolerance adjustments on the wear characteristics of the tire. The axis alignment was checked at 5000 km intervals.

In this experiment the specialized companies performed the field tests and depth measurements of the tire grooves every 5000 km rotated until reaching a final distance of 30000 km traveled, thereby seven measurements of grooves depth were made to complete the test.

The depth measurements of the tire grooves performed in the field experiment are shown in Fig. 4. From it, it is possible to see the wear of the tires during their taxiing. In the rear tires, it is possible to notice greater wear of the tread on the outer edges of the car, the left edge of the left tire (Fig 4 a and c) and the right edge of the right tire. The excessive angle of positive bump on the rear wheels may be the cause of this uneven wear. The front tires presented a more uniform wear compared to the rear ones. Therefore, the front tires show greater wear of the tread on the inner edges of the car.

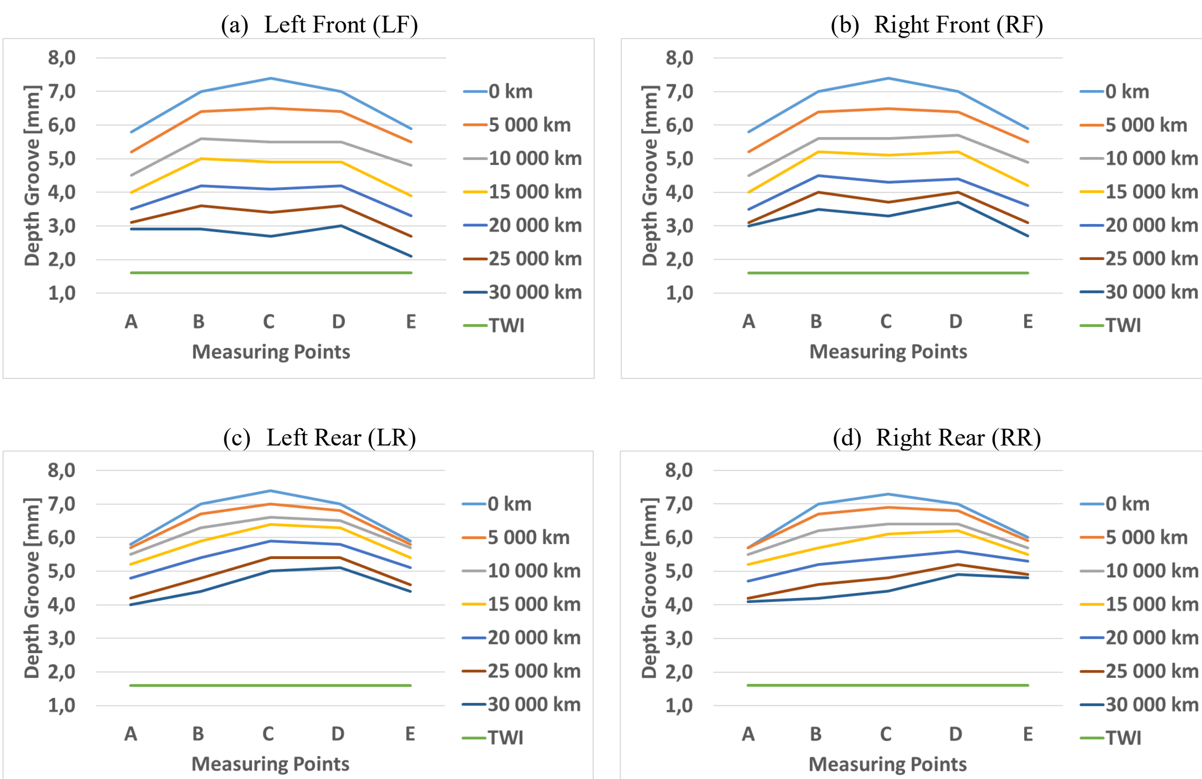

Figure 4. Depth measurements of reference tire grooves.

Figure 5 presents the depth measurements of the proposed tire grooves performed in the field tests. As the reference tires, the proposed tires showed uniform wear of the front tires, but the rear tires had increased wear on the shoulders (Fig. 5 a and b), which may indicate a design error, since both vehicles presented the same irregular wear coming from the positive camber adjustment on the rear wheels.

The car manufacturer of the vehicles that requested the tests was informed and verified that the vehicle has a specific characteristic of the suspension and steering system that promotes this difference in the results.

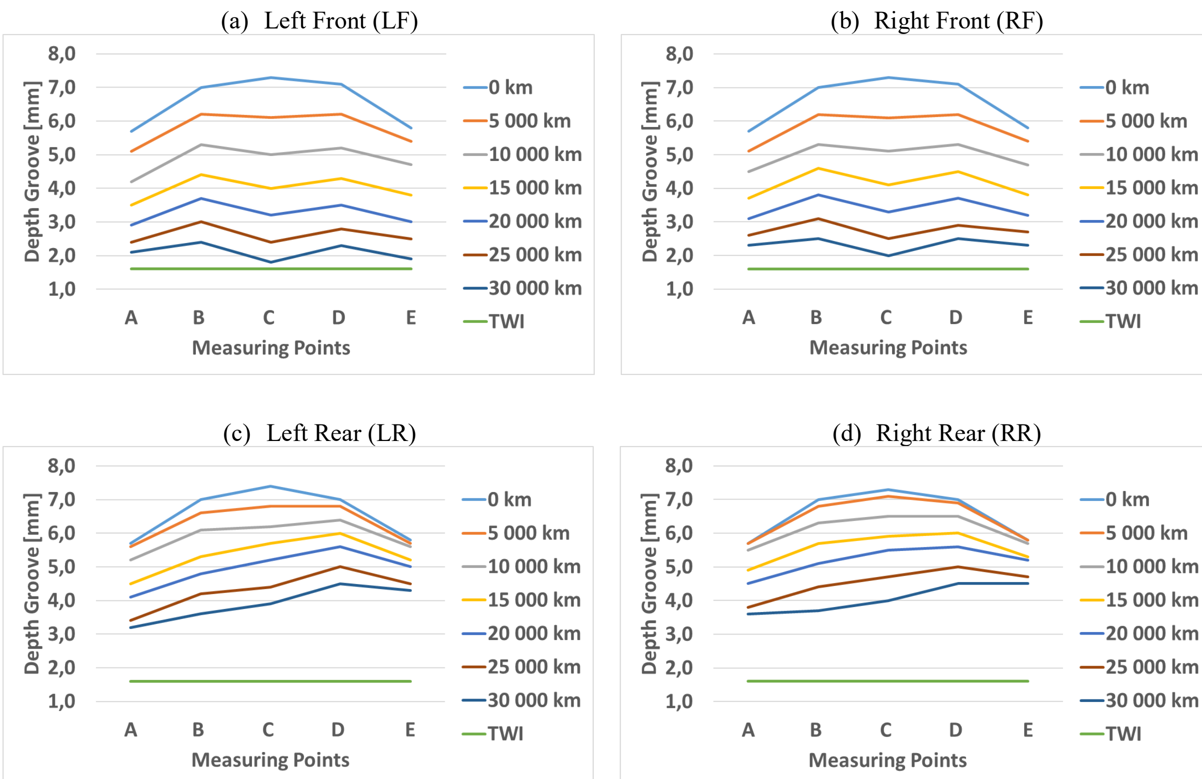

Figure 5. Depth measurements of the proposed tire grooves.

According to Fig. 4 and Fig. 5, it is possible to observe that both the control and proposed tires suffered greater wear in the left rear position when compared to the right rear ones. This is due to the driver weight plus the fuel tank weight mounted on the left side of the vehicle.

Normally the right side tires suffer greater wear than the left side ones, this is due to the slope of roads to the right which promotes a load transfer to the right side of the vehicle. This road condition is very common in Brazil. The main goal of the road slope is to drain rainwater to eliminate or minimize the hydroplaning behavior.

From the control and proposed tire chart depth measurements it is possible to identify that the depth grooves in the center of the tread pattern are greater than on the shoulders with the main purpose to drain the water and increase the lifespan of the tires due to the fact that the central part of the tire is the part that has the longest contact with the road.

The proposed tires presented heavier wear in the center of the tread pattern than the control tire, especially on the front axle, due to the fact that its footprint is more rounded than that of the control tire which has square contact and its tread pattern wears in a more uniform manner.

5.2 Least Squares – Linear Adjustment

In order to verify the effectiveness of the models proposed in this work and the extrapolation made by specialized company, tests were performed with the data measured provided by specialized company. Altogether the specialized company performed a total of seven measurements of tire wear, starting at 0 km and ending with 30000 km travelled. In this way, it was proposed to use the first six measurements to predict the seventh measurement. In the seventh measurement after 30000 km rotated the average height of the TWI measured is 3.2 mm. Therefore, the models should predict for the height of 3.2 mm of the TWI a mileage of 30000 km.

Fig. 6 shows graphically a comparison by linear adjustment between least squares method and linear extrapolation by specialized company. For the lifespan estimated by specialized company, the vehicle should run 27230 km and for the linear curve adjustment 27790 km. Even though the methods are close to each other, they are far from the 30000 km required to obtain a 3.2mm treadwear, that is due to the conservative nature of the linear method which does not take into account some variables the way the nonlinear method does.

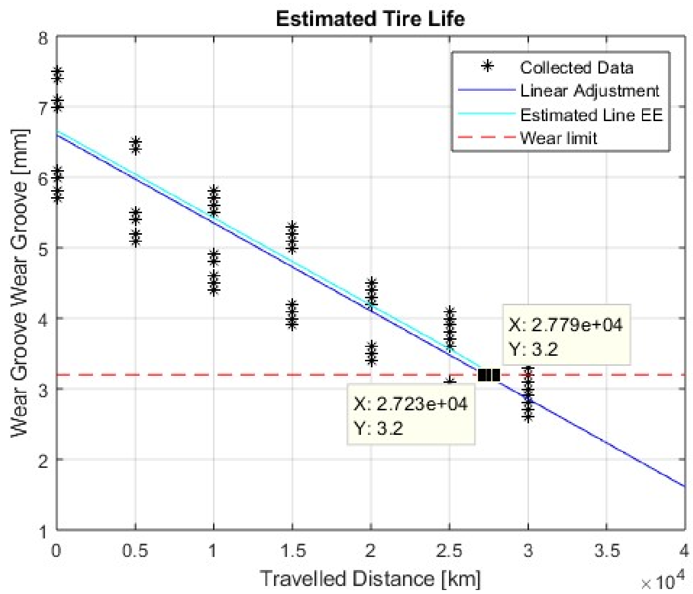

Figure 6. Comparison between Linear Extrapolation and Least Square by Linear Adjustment.

5.3 Maximum Likelihood – Linear Adjustment

The same tests with the data measured by specialized company were performed using the linear adjustment by maximum likelihood method. After 30000 km traveled the TWI is known 3.2 mm, with this mileage the prediction was also performed using the first and sixth measurement.

Fig. 7 shows the comparison of the linear curve fit made by the maximum likelihood method and the extrapolation made by specialized company. According to the estimate by specialized company the vehicle should travel 27790 km and for the linear curve adjustment 28500 km.

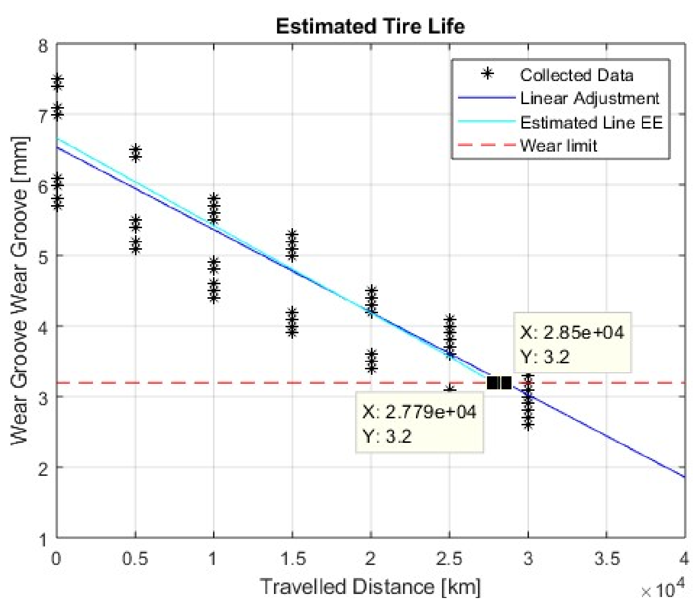

Figure 7. Comparison between Linear Extrapolation and Maximum Likelihood by Linear Adjustment.

5.4 Least Squares – Nonlinear Adjustment

The method of least squares is a technique used to determine an unknown parameter minimizing the sum of the squares of the residuals (Kuan, 2004). The goal is to minimize the difference between the linear equation and the observed points which defines the least squares estimator. The method sums the errors of every observed point. However, in order to avoid the sum of negative numbers, it is preferable to use the sum of squared errors which names the method, the method of minimization of the difference of the squared error.

Fig. 8 shows a comparison between the least squares and the linear extrapolation. As shown in the graph, there is a rise in the travelled distance in the proposed model compared with the current model. The extrapolation model estimates a mileage of 27790 km, while the proposed model a mileage of 29890 km. Due to these results, it can be concluded that the current model is very conservative, however, it devalues the product. This difference of approximately 2300 km is crucial to reduce the cost of the test and increase tire life.

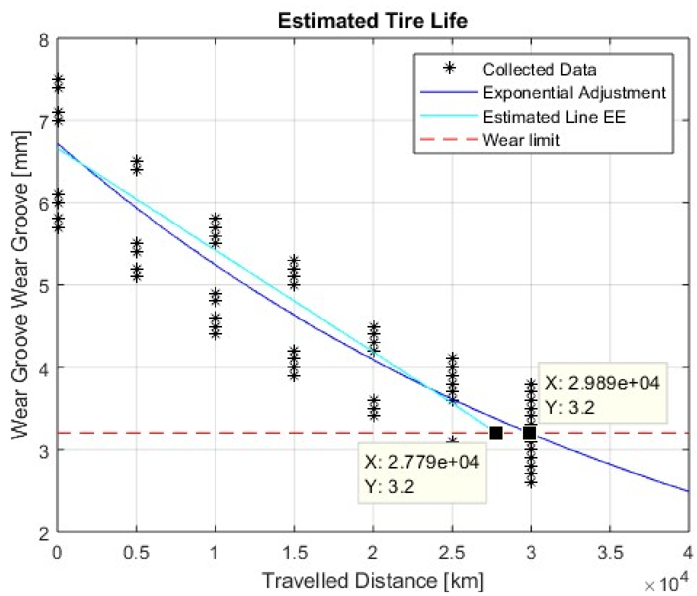

Figure 8. Comparison between Linear Extrapolation and Least Squares by Nonlinear Adjustment.

5.5 Maximum Likelihood – Nonlinear Adjustment

Another method is maximum likelihood which has the function of conditional probability. Given a random sample y in relation to the values x, where y is the tire wear and x is the travelled distance, the parameters estimator θ and variance σ^2 are the unknown parameters of the estimated model (Zeviani et al., 2013). Maximum likelihood is the area of statistical inference, which consists of those methods used to make decisions about a population, divided into two areas: parameter estimation and hypothesis testing.

Fig. 9 shows a comparison between the proposed model (Maximum Likelihood by nonlinear adjustment) and the current model (Linear Extrapolation). As can be seen from the graph, there is a rise in the mileage in the proposed model compared with the current model. The extrapolation model estimates a mileage of 27790 km, while the proposed model a mileage of 31290 km. This difference is approximately 1290 km between the mileage travelled by the tires in the durability test performed on open road and the mileage estimated by the proposed method. The difference between linear extrapolation and the durability test performed is 2210 km.

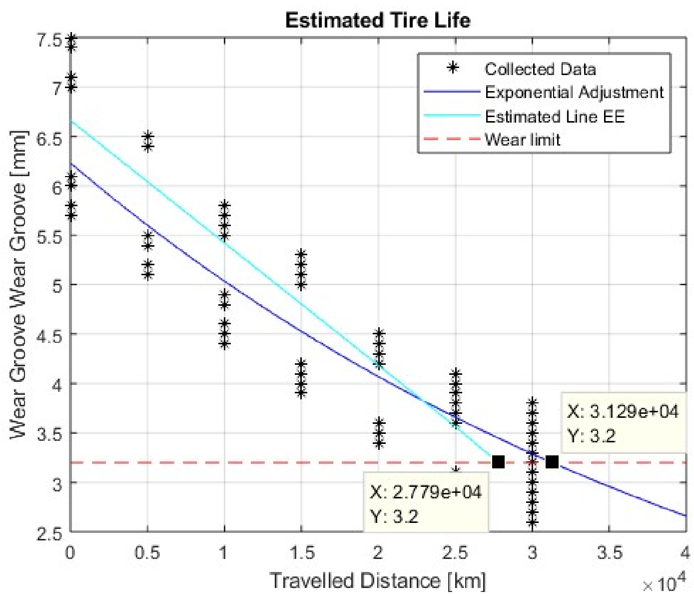

Figure 9. Comparison between Linear Extrapolation and Maximum Likelihood by Nonlinear Adjustment.

In Table 2 we compared the difference between the proposed models and the linear extrapolation used by the specialized companies. As can be seen from Table 2, the models with nonlinear adjustment had a closer test result of the mileage travelled by the test vehicles than the estimation of tire life estimated by specialized company by linear extrapolation method. Even though the maximum likelihood had shown a greater travelled distance, the nonlinear least square model was more precise, getting close to the 30000 km required to reach 3.2mm of wear groove.

Mathematical Model	Travelled Distance (km)	Difference (%)
Least Square - Linear	27790	-7.95
Maximum Likelihood - Linear	28500	-5.26
Least Square - Non Linear	29890	-0.37
Maximum Likelihood - Non Linear	31290	4.12
Specialized Company - Linear Extrapolation	27790	-7.95

Table 2. Comparison between the 30000 km required to reach 3.2mm of wear groove and the proposed models.

5.6 Implementation of software

For the purpose of calculating tire life estimation, an environment was created in MATLAB® to facilitate the analysis of data from the field tests. Fig. 10 shows the layout of the interface created for data analysis.

The interface created in the MATLAB® environment enables easy user interaction with the models proposed in this paper. The mask contains a button called import data used to load the data collected in the experiments. The data is loaded, but the graphical projection is based on the average of the four circumferential points and the five lateral points of the tire tread. The analyzed tire must be chosen and can be any of the four positions of the vehicle. Normally the confidence interval is 95%. Finally, the analyzed method must be chosen, which can be the method of least squares or maximum likelihood. The tire life projection calculations are presented numerically and graphically, facilitating user analysis, which can also compare with the extrapolation model used by specialized companies and car manufacturers. A chart plot button is used to project the graph on the interface screen.

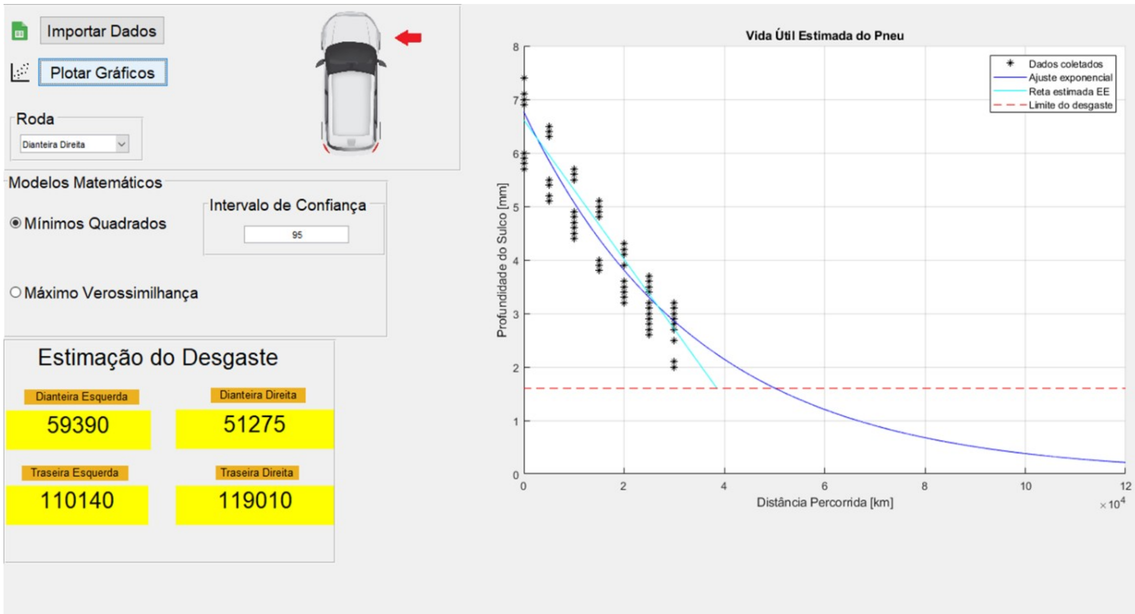

Figure 10. Software interface of Tire Tread Wear test.

The tire wear estimation is done using mathematical models as stated before. These models can extrapolate the collected data and predict the mileage required to reach 1.6mm of depth groove. The interface shown in Fig. 10 presents a comparison between the linear extrapolation and the models proposed in this paper. The tire life estimation of the selected tire used for this analysis is carried out until the TWI (1.6 mm of depth groove) and its main function is to indicate the exact moment necessary to replace the tires, when they no longer provide safety conditions.

6. CONCLUSIONS

This paper presents the comparison between the conventional and the proposed method of estimation of tire life. First, the formula of tire wear is established considering the TWI using two different methods: least square and maximum likelihood. Based on the findings, it was noticed that all the models were adequate to estimate the parameters.

The conventional model estimates a mileage of 27790 km, while the proposed model, using least square a mileage of 29890 km and maximum likelihood a mileage of 31290 km.

Comparing the methods of least square with maximum likelihood which has a complex numerical analysis, it may be seen that the least squares shows a more conservative result. The difference between the proposed model and the current model is a marketing opportunity, because the difference in the mileage evident when comparing the models can be crucial in tire sales against the competitors.

Therefore, the proposed model presented a satisfactory result, according to which it could be recommended to run the tires for 12000 km with intermediary measurements taken every 3000 km to estimate tire service life, which lowers testing time. This model differs favorably from the current model used by companies specializing in tire durability tests, where tires should run at least 40000 km, with intermediary measurements taken every 5000 km to estimate tire service life which takes at least nine weeks and many liters of fuel consumed.

7. ACKNOWLEDGEMENTS

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