A Study of the Wear of Automotive Tires Based on the Theory of Friction and Deformation

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**Abstract.** Tire wear is one of the most important factors that directly affects vehicle safety, fuel efficiency, and operating costs. This paper proposes a method for estimating tire wear using a theoretical model based on friction and deformation. The model is based on the theory of friction and elastic deformation, taking into account the normal pressure and tangential forces that occur at the contact patch between the tire and the road. The calculation takes into account the theory of elastic contact, tire geometry, loading conditions, and the effect of the turning moment. As a result of modeling in the MATLAB/Simulink program, a general wear profile was determined in the friction section of the contact patch. As a result, wear occurs in the slip zone, that is, at the point where the longitudinal elastic force of the tire exceeds the adhesion force between the tire and the ground. The proposed method can be used to determine the service life of the tire.

**Keywords:** Tire, wear, deformation, contact patch, tangential forces, torque, tire elastic force, weight force, pressure distribution

# INTRODUCTION

Car tires are the point of contact between the car and the road, and their technical condition and wear directly affect the safety, stability, controllability, fuel consumption and environmental performance of the vehicle. In recent years, the increase in the number of cars, especially the number of cars and trucks, has further increased the need for methods for predicting the physical and mechanical causes of tire wear and mileage.

Typically, tire mileage is determined experimentally or estimated using simplified mathematical expressions. However, such methods do not adequately account for the real physical and mechanical phenomena in the tire-road contact patch, elastic deformation, tangential forces, and pressure distribution. This reduces the reliability of the resulting wear profiles. [3, 19].

Recent studies have proposed various approaches to estimate tire wear. For example, Kim et al. [4] presented a method to feed data from internal inertia, pressure, and load sensors into a computational model, [7] Liu et al. used a one-dimensional convolutional neural network to analyze vehicle signals (i.e., acceleration, vertical load, and pressure). In [20], researchers developed a high-precision system by extracting features from vibration signals and processing them using the CatBoost classifier algorithm. In addition, 3D optical scanning technologies [9] and camera-based tracking systems [18] have been used to monitor physical changes on the tire surface. A number of studies have been conducted to determine tread wear by analyzing the particulate matter emitted by tires [6, 7]. Further studies have developed a theory of tire tread deformation and particle separation dynamics [2, 14].

The model developed by J. F. Archard is designed to determine the abrasive wear caused by friction against a surface [1]. This model uses a mathematical method to describe the losses that occur during the relative motion of the contacting surfaces [1].

The Ree model is an empirical function that describes the wear of elastic surfaces due to friction [15]. This function depends on the sliding velocity of the elastic element and the pressure on the contact surface. However, since it does not take into account the distribution of pressure and velocity along the contact surface, its application requires integration with complex models.

The Hans B. Pacejka model was developed to empirically express the relationship between the friction forces of the tire on the road and the slip angle [13]. The model is used to evaluate the interaction of the tire with the road under various driving conditions (e.g., during turns, acceleration and braking).

As a result of the analysis of the conducted studies, it was found that most existing methods for determining the mileage of tires require the use of testing equipment, which increases the cost and does not take into account the physical processes on the supporting surface.

To overcome these shortcomings, this paper proposes a calculation method for determining tire wear based on the theory of friction and deformation. By studying the forces of interaction between the tire and the road surface, it is possible to determine the deformation of the tire tread and the slip zone in the contact patch. This allows for a more accurate assessment of the tire wear process and mileage.

**RESEARCH OBJECTIVE**

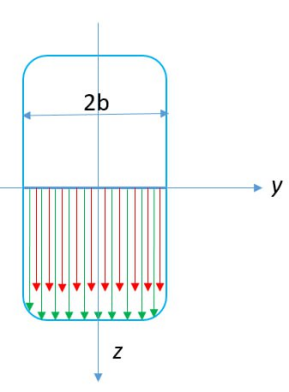
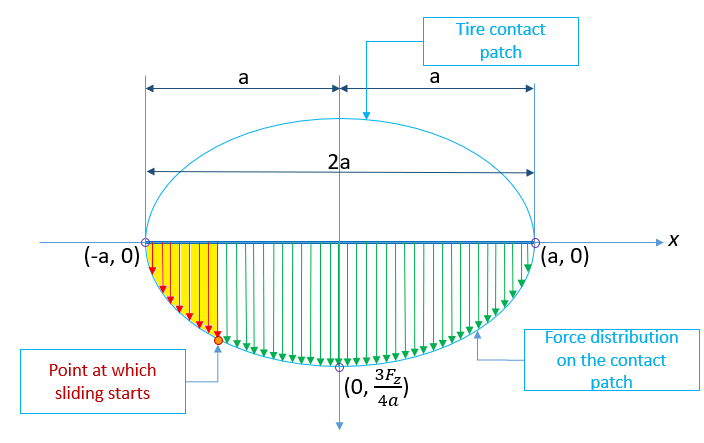
The objective of this study is to determine the wear of a car tire using a calculation method based on the theory of friction and deformation. The analysis is aimed at determining the normal pressure, sliding path and tangential forces occurring in the sliding zone between the tire and the road.

**METHODOLOGY**

The wear process that occurs between automotive tires and the road surface is governed by two fundamental physical phenomena: friction and deformation. These mechanisms result in the detachment of micro-particles from the tire surface, a phenomenon facilitated by the combined effects of tangential forces, elastic strain, and relative slip motion within the contact area [12].

The portion of the tire that directly interfaces with the road—termed the "contact patch"—constitutes the principal physical domain in which tire-road interaction occurs [12] (see Figure 1). The total force transmitted between the vehicle and the road is concentrated within this region. The tire contact patch can be subdivided into two distinct areas:

* **Adhesion zone**: There is no relative motion between the tire and the road surface. Forces are transmitted entirely through elastic deformation.
* **Slip zone**: Relative sliding occurs between the surfaces, resulting in significant frictional forces, energy dissipation, and intensified tread wear.



**FIGURE 1.** A schematic representation of the tire-road contact patch, pressure distribution, and slip onset region

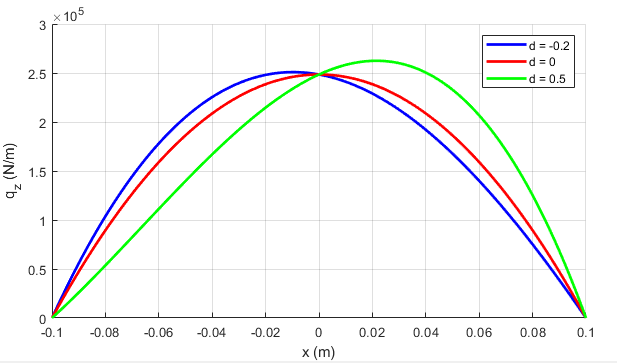
The figure above (Fig. 1) schematically shows the distribution of the weight force in the tire contact patch. The shape and size of the tire contact patch with the road change over time. The pressure distribution in the contact patch during movement is symmetrical. That is, when the tire is deformed and dynamically moving, asymmetry occurs, which means that the center of pressure shifts forward or backward from the wheel axis. Thus, a parabolic pressure distribution is insufficient to determine this wear profile.

Such an approach was proposed by Jacob Svendenius and Björn Wittenmark in their study "A model for a flexible brush tire" [17]. In their study, the pressure distribution across the contact patch is modeled using an asymmetric third-order polynomial function. The proposed pressure distribution is expressed as follows (1) [17]:

(1)

where: —vertical force per unit length (N/m); — vertical force (N); — half of the contact length (i.e.,); — the asymmetry coefficient, representing the shift of the pressure center within the contact zone.

In the above expression, the first multiplicative term, , defines a parabolic pressure shape that reaches its maximum at and becomes zero at the boundaries . The second term, , introduces asymmetry into the pressure distribution and accounts for the shift in the pressure profile [17].



**FIGURE 2.** Distribution of vertical force per unit length along the tire–road contact patch

If , the model is symmetric, and the maximum pressure occurs at the center of the contact patch. However, if , the pressure center shifts forward along the contact length - typically corresponding to a traction scenario. Conversely, if , the pressure center shifts rearward, which represents a braking condition [17].

One of the key advantages of this model is that it employs a normalized formulation, which ensures that the total vertical force per unit length remains equal to regardless of the selected value of .

(2)

This condition guarantees the conservation of the total normal force for any vertical force profile defined per unit length. As a result, the parameter only alters the geometric distribution of the vertical force per unit length but does not affect the overall contact force [9, 17].

The asymmetric vertical force model per unit length not only provides a closer approximation to real-world conditions but also enables more accurate analysis of the resulting moment and slip behavior. For instance, the moment generated due to the shift in the pressure center can be expressed (3) as follows [17, 10, 11]:

(3)

The resulting integral is given as follows:

(4)

The integral is split into individual terms as follows:

(5)

Each integral is now evaluated individually as follows (5):

1. (6)
2. (7)
3. (8)
4. (9)

Accordingly, the parameter can be determined in reverse form (10):

(10)

As the wheel rotates, tangential forces are generated at the interface between the tire and the road. These forces produce a torque within the contact patch. This torque represents the reaction moment that the tire exerts on the road surface due to the deformation of the tire material during rotation.

In the formula ​, the coefficient “5” arises from the analytical integration of the moment generated by an asymmetric pressure distribution within the tire contact zone. Specifically, when a parabolic pressure profile in the -direction is modified by an asymmetry term ​, the closed-form solution of the tangential moment integral yields this factor.

This coefficient enables a direct relationship between the displacement of the pressure center and the resulting moment in the model.

To determine the boundary between slip and adhesion, the force equilibrium at each point along the contact patch is analyzed. When the elastic deformation of the tire reaches the onset of sliding, the tangential elastic force in that local element becomes equal to the corresponding frictional force. This condition allows the identification of the slip onset location, denoted as , within the contact zone.

Slip initiation occurs when the elastic deformation of the tire reaches a threshold where it balances the maximum available friction force. This equilibrium condition is described by the following algebraic equation [17]:

(11)

where: — stiffness coefficient; — slip ratio; — half-length of the contact patch; — coefficient of adhesion (friction coefficient); —vertical pressure value at the slip onset point .

The equation can be rewritten in expanded form as follows:

(12)

This expression results from solving the square root–based rational equation and takes the following form:

(13)

sliding friction force in the slip zone:

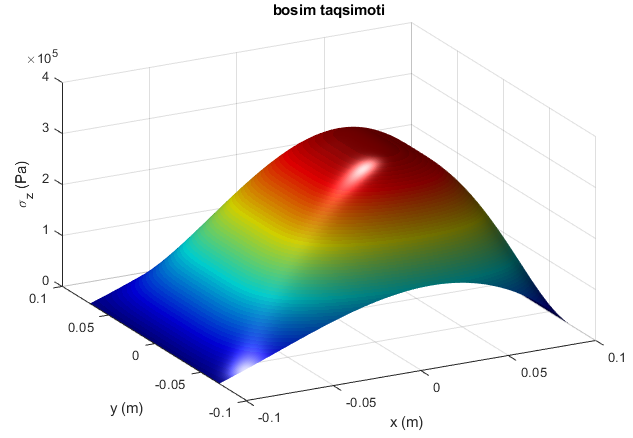
(14)

The normal pressure ,​ generated in the contact zone between the tire and the road is typically modeled as a distribution along the direction of motion, i.e., along the -axis. However, the actual contact zone is not one-dimensional; it is a two-dimensional surface bounded in both the longitudinal () and lateral () directions.

In reality, the pressure is not uniform across the width of the tire surface (the -axis); rather, it tends to decrease from the center toward the edges. By incorporating the exponential decay of pressure away from the center in the lateral direction, the pressure distribution can be expressed as follows:

(15)

To accurately represent the overall contact pressure distribution from both physical and mathematical perspectives, the pressure must vary not only along the longitudinal direction () but also across the lateral direction () of the tire.

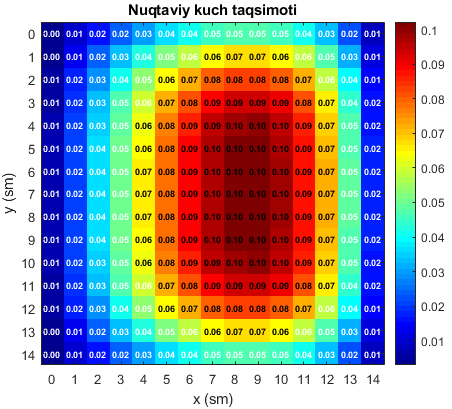
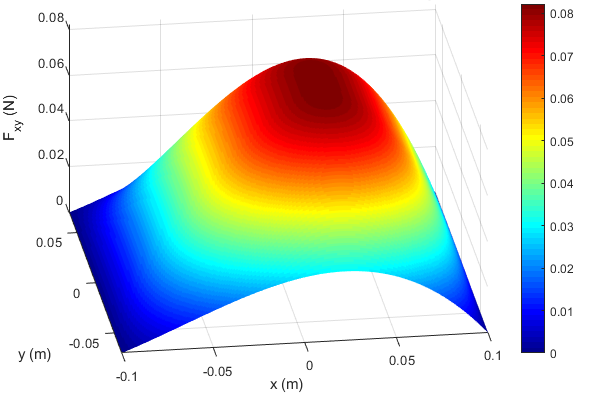


**FIGURE 3.** Three-dimensional pressure distribution over the tire–road contact surface

The total normal force exerted by the tire on the road is determined by integrating the distributed normal pressure over the contact surface. This force is expressed through a two-dimensional integration over the contact zone as follows [16]:

(16)

Moreover, the pressure at each point within the contact area defines the local force contribution, and the total tire force is obtained by integrating these contributions over the entire contact patch.



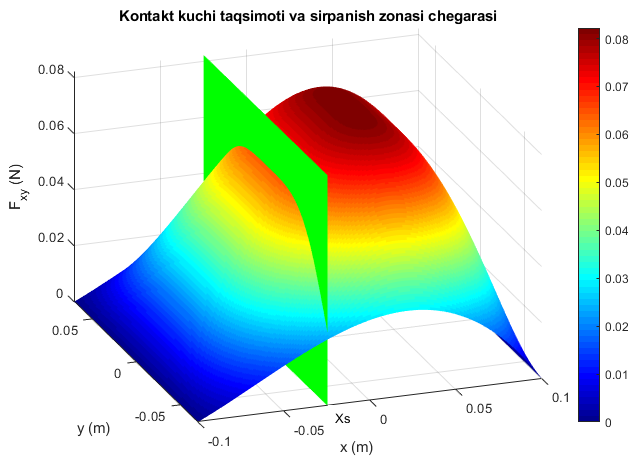
**FIGURE 4.** Three-dimensional and heatmap visualization of pointwise tangential force distribution on the contact surface

The figure illustrates the distribution of tangential forces across the contact patch. The 3D plot on the left shows the force density, which depends on the shape of the contact area and the applied load. On the right, the contact surface is divided into a 15×15 grid, with the force magnitude at each point represented numerically. The force is highest at the center and decreases toward the edges.

In the slip zone (), the tangential force density generated over the contact surface represents the frictional forces arising from the relative motion (slip) between the tire and the road. This force density is directly related to the pressure distribution and the frictional characteristics of the contacting materials, and it is defined by the following expression [16, 19, 20]:

(17)

This 3D plot shows the distribution of tangential forces over the contact surface. The color gradient indicates the force magnitude (blue - low, red - high). The green plane represents the boundary of the slip zone at the point . This boundary is determined based on contact elasticity and the level of friction.



**FIGURE 5.** Vertical force distribution and slip zone boundary point

Material wear occurs at the contact interface between the tire and the road due to elastic deformation and frictional effects. A widely used approach to quantify this physical phenomenon is the Archard model, which describes the volume of material loss resulting from pressure-induced deformation during sliding contact. The general form of the Archard wear model is expressed as follows:

(18)

This expression represents the material loss over the slipping region of the tire, taking into account the two-dimensional pressure distribution across both the longitudinal and lateral directions of the contact surface. The Archard model is used in the brush model but includes a portion of the tire in the sliding zone where gravity forces are applied to account for tire wear.

# CONCLUSION

This study determines the wear profile based on the distribution of normal pressure and tangential forces in the tire contact patch. The length of the slip zone in the contact patch is determined using an analytical equation. Taking into account the change in pressure in the contact patch depending on the vehicle's movement, the model allows determining tire wear under conditions close to real ones.

The results show that tire wear depends on many factors, the main ones being tire load, tire stiffness, road conditions, wheel torque, and slip zone length. The proposed method for calculating tire wear uses the theory of friction and deformation to determine their mileage.

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