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A study of the effect of vehicle exterior design on tyre wear and life: modelling of aerodynamic mechanisms and regression model analysis

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Abstract. Tyre wear is a core factor affecting driving safety and operating costs. Conventional studies have focused on traditional factors such as tyre materials, suspension systems and driving behavior, while neglecting the deeper mechanisms by which vehicle exterior design affects tyre wear through aerodynamic pathways. This study aims to construct a theoretical framework to reveal how aerodynamic design parameters (e.g., front and rear wings, diffusers, etc.) affect tyre friction and slip rate by changing the downforce distribution, and ultimately affect tyre wear rate and service life. By integrating Bernoulli's equation and the multiple linear regression method, a tyre life prediction model covering key variables such as friction, average speed, underbody height, road condition and slip rate is established, and the differential wear mechanisms such as thermo-mechanical fatigue and grinding loss caused by front and rear axle underpressure imbalance are also deeply analyzed. The results show that the aerodynamic effect induced by exterior design has a decisive influence on tyre wear patterns, and the theoretical model proposed in this paper provides an innovative analytical framework for quantitatively assessing this effect. Although the specific coefficients of the model are yet to be calibrated and verified by Computational Fluid Dynamics (CFD) simulation and real vehicle test data, the theoretical results of this study are of great significance for optimizing vehicle design, extending tyre life and reducing operating costs.

Keywords: tyre wear, aerodynamics, downforce, regression model, slip rate

1. Introduction

The service life of vehicle tyres is one of the key indicators for measuring the economy and safety of vehicle use, and their wear and tear is directly related to driving safety, fuel consumption and operating costs. According to the International Tyre Association Statistics [1], the cost of commercial vehicle tyre replacement accounts for about 18-23% of the total operating costs, while the cost of tyres for high-performance passenger cars can account for more than 30% due to frequent and intense driving. In Formula 1, the life of a single tyre is only 80-120 km, and tyre expenditure accounts for 8% of the team's annual budget [2]. Therefore, an in-depth study of tyre wear mechanisms and life prediction is of great significance to vehicle design and safety management.

For a long time, academic and engineering research on tyre wear has focused on traditional factors, such as tyre material and structure [3], vehicle load and suspension system [4], driving speed and driving habits [5], and road conditions and climate [6]. However, a factor that has not been fully explored is vehicle exterior design and the aerodynamic effects it produces. Exterior design elements (e.g., front wings, rear wings, diffusers, side skirts and flat floorboards) significantly affect the vertical loads and ground friction of tyres by altering the distribution of pressures above and below the bodywork, which may accelerate or retard tyre wear [7]. For example, the Tesla Cybertruck reduced turbulence by levelling the chassis design and reportedly increased its tyre life by 15% [8].

Despite the existence of individual cases, there is a serious lack of systematic research in the existing literature on the quantitative relationship between aerodynamic parameters (e.g., wake angle, diffuser shape) and tyre wear [9]. There is a clear knowledge gap between traditional research paradigms and emerging aerodynamic perspectives. Therefore, this study aims to fill this gap by combining aerodynamic theory with statistical analysis methods to quantitatively analyse the effects of different exterior design parameters on tyre life. Firstly, this study will calculate the downforce and tyre force based on Bernoulli's equation and aerodynamic principles; then, a multivariate linear regression model will be constructed to analyse the quantitative effects of parameters such as chassis height, diffuser type, spoiler angle, and so on, on tyre wear. Through this approach, this study not only provides a new theoretical perspective for understanding tyre wear, but also provides an empirical reference for the optimization of automotive design and the scientific selection of tyres, which is expected to provide a decision-making basis for the reduction of the total life cycle cost of automobiles.

2. Introduction to the principle

2.1. Definition of tyre life

The life of a tyre can be defined from several perspectives, of which, in this paper, the length of use of the tyre is considered as the life of the tyre. However, this method of definition is affected by the frequency of use of the tyre, and therefore will have a large error. In addition, the tread thickness of a tyre can be used to determine it, but this type of data is usually expensive to obtain and is greatly affected by external factors, resulting in a large error in the measurement results. The above definitions are not applicable to this study. Therefore, in this study, the service life of a tyre is defined as the distance between the time the vehicle is driven continuously and the time when the tyre is worn out and cannot be driven safely. We can have the advantage of low acquisition cost and small error by continuous driving experiment.

Tyre life: L_i

2.2. Regression model for tyre life

Through careful consideration, tyre wear is influenced by the vehicle's own design parameters and environmental factors, of which, according to this study, the own design parameters include: f, V_i, and H.

Environmental factors include T_i: Road conditions (road temperature, etc.)

Combined factors include η: Slippage rate Therefore, through the regression analysis model, there is a linear correlation between the life of the tyre and the above variables:

$$L_i = \beta_0 + \beta_f + \beta_2 v_i + \beta_3 H + \beta_4 T_i + \beta_5 \eta + \varepsilon_i \tag{1}$$

L_i: Tyre life; f: friction; V_i: Average travelling speed; H: underbody height; T_i: Road conditions (road temperature, etc.);

η: slip rate slip rate.

3. Analysis of tyre wear mechanisms

According to the Research on the Mechanism and Conditions of Polygonal Wear of Automobile Tyres [10], when the front downforce of the vehicle > rear downforce, the front wheels will experience overload wear due to excessive vertical load, which triggers granularity, which leads to the formation of a vicious circle of granule detachment, and a surge in the rate of wear; the rear wheels will experience skid wear due to insufficient vertical load, and the tyres are prone to an abnormally smooth wear state when they are skidding, with some regions experiencing a heat Concentration of heat in some areas leads to local blistering. When the front downforce is greater than the rear downforce, the front wheels wear due to thermo-mechanical fatigue and the rear wheels wear due to grinding loss [11].

When the front downforce is lower than the rear downforce, the front wheels will break through the grip limit easily when the vehicle brakes due to the lack of vertical load, and locking occurs, which generates high temperature on the very small contact surface, triggering the flat spot wear and accelerating the wear rate; the rear wheels will be subjected to very high driving force and vertical load, and compound load wear occurs, and at this time, the rear wheels will be operated at a very high temperature, which is easy to appear blisters, and the formation of cavities leads to The rear wheels run at very high temperatures and are prone to blistering, forming cavities and causing the surface rubber to peel off, resulting in very high wear rates. When the front downforce is less than the rear downforce, the rear wheel wears due to thermal failure under compound stresses and the front wheel wears due to sliding loss in the absence of grip.

4. Aerodynamic theory and modelling calculations

When a vehicle is in motion, air flows around the body, creating a pressure difference that creates a downward force on the vehicle, a force known as downforce. The common body parts that provide downforce for the vehicle are the front wing, rear wing, diffuser, side skirts, and floor pan. The front wing provides downforce to the front part of the vehicle and directs the airflow to the subsequent parts of the body. The rear wing provides the rear part of the vehicle with downforce, which is essential for maintaining stability at high speeds. The diffuser works in conjunction with the floorboards, which are designed to manage the underbody airflow when the vehicle is driven by means of flattening and specific shapes to create a "ground effect". The diffuser is one of the main sources of downforce for the vehicle in order to accelerate the airflow out of the floorboards in the middle and rear parts of the vehicle chassis. The side skirts work in conjunction with the air dam (front spoiler) to prevent airflow from entering the underbody from the sides, maintaining a low-pressure area under the chassis. Downforce increases the contact force between the tyre and the ground, making the tyre more stable, and may also affect the rate of tyre wear [12].

In aerodynamics, the Navier-Stokes equations are used to describe fluid motion. The core idea of this set of equations is based on the basic principles of physics, such as conservation of mass, momentum and energy, which establishes the relationship between the velocity field, pressure field, density field, and the external forces (e.g., gravity) of the fluid, with special consideration of the effect of viscous forces (similar to internal friction), but also because the physical quantities involved in the equations are not easy to But also because the physical quantities involved in this equation are not easy to obtain a large amount of data, there are many variables affecting the data, and as a non-linear differential equation, it is exceptionally difficult to solve, so this experiment does not use it as a research, Bernoulli's equation has the characteristics of a brief introduction and a clear physical meaning, so this experiment uses it as a tool for calculating the change of the pressure of the air around the body of the car. Bernoulli's equation describes the relationship between the velocity and pressure of a fluid (air) in its basic form:

$$P + \frac{1}{2}\rho v^2 = C \quad (2)$$

P: Air pressure (Pa); ρ: the air density (kg/m³); v: Air velocity (m/s).

When air flows under the car or through the diffuser or spoiler, the flow rate increases and the pressure decreases, and according to Bernoulli's principle, this creates a downward force.

$$F_{down} = \frac{1}{2}\rho v^2 C_L A \quad (3)$$

ρ: the air density; v: speed of the car; C_L: Lift coefficient (determined by appearance); A: windward side (of an area)

As shown in Table 1, qualitative effects of exterior design parameters on lift coefficients are listed.

Table 1. Qualitative effects of exterior design parameters on lift coefficients

Parameter Changes	Parameter Changes	Parameter Changes	Parameter Changes
tail attack angle	increase	Increased negative value (increased downforce)	Increasing the windward angle deflects the airflow more strongly and increases the pressure difference between the upper and lower surfaces.
Diffuser angle	increase	Increased negative value (increased downforce)	Accelerates underbody airflow more efficiently and strengthens the Venturi effect, resulting in a wider range of underbody low-pressure zones and lower pressures.
Front Lip Height	decrease	Increased negative value (increased downforce)	Reducing the flow of high-speed airflow into the underbody reduces the underbody pressure; at the same time, increasing the front windward surface increases the pressure in the front high-pressure zone.
Side skirt height	decrease	Increased negative value (increased downforce)	Better sealing of the sides of the car body prevents high-pressure airflow from surging into the underbody, thus maintaining an ideal low-pressure condition underneath the car.
Ground Clearance	decrease	Increased negative value (increased downforce)	Enhanced "ground effect" restricts airflow underneath the vehicle, making it faster and less stressful, creating extreme downforce.
Body surface flatness	flatter	Increased negative value (increased downforce)	Reduced turbulence and airflow separation allows airflow to flow more smoothly through the body, favouring the formation and maintenance of a low-pressure zone.

4.1. Travelling friction

The following formulas are used to calculate the sliding friction when an object is subjected to an additional downward force:

$$f = \mu R \quad (4)$$

$$R = W + F_{down} \quad (5)$$

4.2. Slip rate

Tyre slip rate is an important parameter that describes the degree of relative sliding between the tyre and the ground, which directly affects the acceleration, braking and steering performance of the vehicle [13]. The two main factors mentioned in the above regression model, "own design parameters" and "environmental factors", have a direct influence on the slip rate, and the degree of their influence depends on the specific working conditions. Among the two factors, the influence of own design parameters on slip rate is controllable, such as adjusting the vehicle tyre pressure/formulation/tread, suspension softness, ABS sensitivity, torque distribution, etc., which can artificially control the slip rate, but the environmental factors cannot be artificially controlled during the driving process, such as different friction coefficients of non-material road surfaces, climate, etc., which directly affects the slip rate [14].

Driving (acceleration): slip rate (%) = (wheel speed - actual vehicle speed) / actual vehicle speed] * 100%

Braking (deceleration): Slippage (%) = [(actual vehicle speed - wheel speed) / actual vehicle speed]* 100%

$$\eta = \left| \frac{v_L - v_A}{v_A} \right| \times 100\% \tag{6}$$

η: Slippage rate; V_L: Wheel rotation linear velocity; V_A: The actual speed of the vehicle;

Pure rolling: slip rate = 0%

Full lock-up (hold-up): slip rate = 100%

Complete idling (skidding): slip rate → ∞ (Because the actual speed of the vehicle may be close to 0)

4.3. Regression model

$$L_i = \beta_0 + \beta_f + \beta_2 v_i + \beta_3 H + \beta_4 T_i + \beta_5 \eta + \varepsilon_i \tag{7}$$

L_i : Tyre life

f: friction

V_i: Average travelling speed

H: underbody height

T_i: Road conditions (road temperature, etc.)

η: slip rate

4.4. Preliminary analysis of the model

As the model coefficients are yet to be calibrated with experimental data, this paper only provides a theoretical analysis of the expected direction of influence of each variable of the model. Based on the aforementioned mechanism:

Friction (f): the regression coefficient β_1 is expected to be negative. An increase in friction, which usually results from an increase in downforce, increases tyre wear and is negatively correlated with life Li.

Average travelling speed (V_i): the coefficient β_2 is expected to be negative. The higher the speed, the more work and heat are generated by the friction between the tyre and the ground, increasing wear and reducing life.

Underbody height (H): The coefficient β_3 is expected to be positive. An increase in underbody height usually reduces aerodynamic effects, downforce and friction, and may increase life, so there is a positive correlation.

Road conditions (T_i): This is a composite variable. For example, an increase in road temperature may result in a negative coefficient β_4 (high temperatures soften rubber and increase wear); an increase in road roughness may also result in a negative coefficient.

Slippage (η): the coefficient β_5 is expected to be negative. The slip rate is a direct measure of the degree of sliding friction of the tyre; the greater the slip rate, the more serious the wear and the shorter the life.

The significance of the model and the precise quantification of the contribution of each variable are to be completed by fitting the experimental data in subsequent studies.

5. Conclusion

This study systematically investigates the mechanisms by which vehicle exterior design influences tyre wear and life through aerodynamic effects, and constructs a corresponding quantitative theoretical analysis framework. The main core conclusions are as follows: (1) The downforce balance between the front and rear of the vehicle is crucial in determining the tyre wear pattern and rate. The study reveals that front and rear pressure imbalance leads to very different forms of excessive wear on front and rear tyres, such as granulation triggered by overloading of the front wheels, smooth wear and blistering caused by slipping of the rear wheels, or flat spot wear produced by locking of the front wheels and peeling caused by heat exhaustion of the rear wheels, etc., which are the mechanisms that can significantly shorten the tyre life. (2) In this paper, the physical and chemical processes of tyre wear (e.g., thermo-mechanical fatigue, grinding loss) are analyzed in detail under different downforce ratios (front > rear, front < rear), providing a solid theoretical basis for the diagnosis and prevention of abnormal wear. (3) The study successfully established a multiple linear regression model incorporating key aerodynamic parameters (embodied by friction f and slip rate η), linking the tyre life (L_i) with variables such as average driving speed (V_i), underbody height (H), and road conditions (T_i), which provides a new research paradigm for quantitative prediction and analysis of tyre life.

It must be noted that this paper is a theoretical and modelling framework study, and the proposed regression model (Equation 1) has not been fitted and validated with real data. Due to the practical difficulties of obtaining large-scale, high-precision real-vehicle tyre wear and aerodynamic coupling data, such as high cost, corporate secrecy and complex control of the test environment, the regression coefficients of the variables in the model (e.g., β_0, β_f, β_2, …, β_5) and their significance levels are still unknown parameters at present. In addition, this study attributes the complex aerodynamic effects mainly to the influence of friction (f), which may ignore potential factors such as direct thermal effects of airflow on tyres (e.g., cooling/heating), aerodynamic shear, and dynamic coupling with the suspension system. Meanwhile, the definition of the variable "road condition (T_i)" is broad, covering multiple factors such as road surface material, temperature, humidity, etc., which are difficult to be precisely quantified, and these are the areas where the model of this study needs to be improved. Future research can follow the following paths: (1) Model validation and calibration: the first task is to use Computational Fluid Dynamics (CFD) simulation to numerically simulate different exterior designs and obtain key input parameters such as downforce coefficients; at the same time, tyre wear data can be collected through indoor bench tests or real vehicle tests at limited sites to calibrate and validate the regression model. (2) Innovation of research method: based on obtaining sufficient data, machine learning algorithms (e.g., random forests, neural networks) can be used to deal with the complex non-linear relationships that may exist between variables, and construct a prediction model with higher accuracy than the linear regression model. (3) Model expansion and deepening: extend the current steady-state model to dynamic conditions such as acceleration, braking, cornering, etc., and study the transient aerodynamic effect; and include the tyre's formula, structure, air pressure and other parameters as variables in the model to form a more comprehensive prediction system. (4) Application and Translation Research: After the model has been fully validated, further cost-benefit analysis can be carried out to quantitatively assess the extension of tyre life and economic value enhancement brought about by aerodynamic optimization, to provide direct decision-making support for the field of automotive design.

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