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Review

Tire–Road Interaction: A Comprehensive Review of Friction Mechanisms, Influencing Factors, and Future Challenges

Adrian Soica and **Carmen Gheorghe** *

Department of Automotive and Transport Engineering, Transilvania University of Brasov, 500036 Brasov, Romania
* Correspondence: carmen.gheorghe@unitbv.ro

Abstract

Tire–road friction is a fundamental factor in vehicle safety, energy efficiency, and environmental sustainability. This narrative review synthesizes current knowledge on the tire–road friction coefficient (TRFC), emphasizing its dynamic nature and the interplay of factors such as tire composition, tread design, road surface texture, temperature, load, and inflation pressure. Friction mechanisms, adhesion, and hysteresis are analyzed alongside their dependence on environmental and operational conditions. The study highlights the challenges posed by emerging mobility paradigms, including electric and autonomous vehicles, which demand specialized tires to manage higher loads, torque, and dynamic behaviors. The review identifies persistent research gaps, such as real-time TRFC estimation methods and the modeling of combined environmental effects. It explores tire–road interaction models and finite element approaches, while proposing future directions integrating artificial intelligence and machine learning for enhanced accuracy. The implications of the Euro 7 regulations, which limit tire wear particle emissions, are discussed, highlighting the need for sustainable tire materials and green manufacturing processes. By linking bibliometric trends, experimental findings, and technological innovations, this review underscores the importance of balancing grip, durability, and rolling resistance to meet safety, efficiency, and environmental goals. It concludes that optimizing friction coefficients is essential for advancing intelligent, sustainable, and regulation-compliant mobility systems, paving the way for safer and greener transportation solutions.

Keywords: tire–road interactions; friction coefficient; tire models; vehicle dynamics; TRFC influencing factors; tire wear particles; tire materials

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1. Introduction

Understanding tire–road interaction is necessary in order to ensure safety because high friction coefficients can reduce braking distances and improve vehicle control, especially in adverse conditions such as wet or icy roads. Friction is explained in [1] as a sum of adhesion (molecular), hysteresis (deformation), and cohesion (wear). Adhesion dominates on smooth, dry surfaces; hysteresis is key on rough or wet surfaces; the role of cohesion is minimal. Conditions like wet asphalt reduce TRFC due to decreased adhesion. Reference [2] identifies that tire composition (rubber type, tread, pressure, and temperature), road texture (micro- and macro-texture), external agents (water, ice, and dust), and sliding speed all crucially affect tire–road friction. The friction coefficient between tire and road is influenced by a complex interplay of factors, including tire composition [3], inflation pressure [4], temperature [5], road surface texture [6], environmental conditions (wetness, ice, and dust) [7], and relative motion. These parameters determine the balance between adhesion, hysteresis, and wear-based friction mechanisms. Accurate estimation and optimization of friction are critical for vehicle safety, energy efficiency, and performance, particularly in varying climatic and operational conditions. Tires with lower rolling resistance, often a trade-off for high grip, improve fuel efficiency. However, maintaining a balance between grip and rolling resistance is essential to ensure safety without compromising fuel economy [8]. The goal of improving the environmental sustainability of sustainable tire materials, focusing on bio-based rubbers and green manufacturing processes, is presented in [9]. According to the EURO 7 pollution regulations, the particles generated by the wear of tires must be limited. In [10] the authors analyzed tires with different treads and their effects on tire wear control.

The main novelty of this narrative review lies in its capacity to synthesize current findings while simultaneously identifying persistent research gaps within a complex and dynamic field. These gaps, presented in Figure 1, include the real-time estimation of the tire–road friction coefficient and the modeling of combined environmental effects, which remain insufficiently developed; the influence of current materials such as silica and nanocomposites on friction, which is not yet fully understood, particularly under variable conditions; the challenges generated by electric and autonomous vehicles, which involve distinct loading patterns, higher torque, and specific dynamic behaviors; as well as the implications of the Euro 7 regulations, which for the first time impose limits on particle emissions resulting from tire wear and therefore require a reorientation and systematic guidance of research efforts.

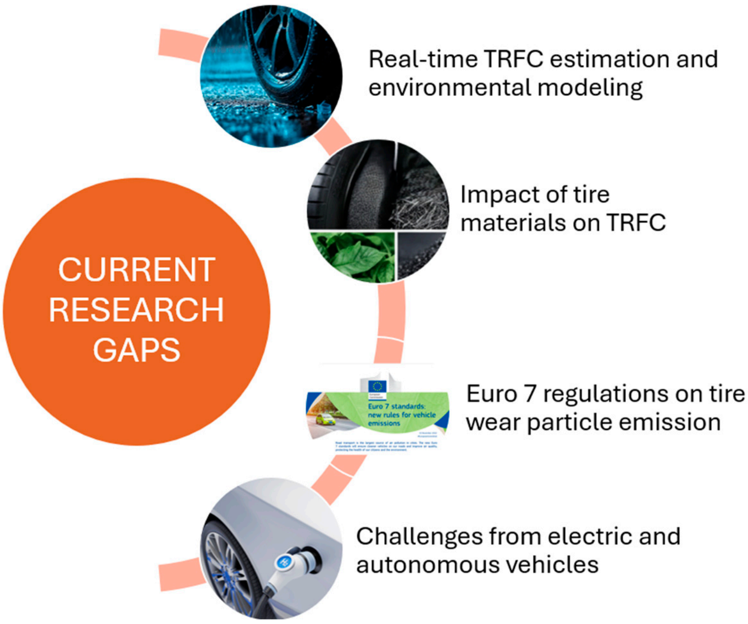


Figure 1. Mapping the current research gaps in the TRFC field.

The significance of this work is multifaceted, extending beyond a theoretical understanding of friction and encompassing several critical dimensions. From the perspective of vehicle safety, TRFC directly affects braking distances and vehicle control, especially under adverse conditions, which makes its precise estimation and optimization essential. At the regulatory level, the study provides timely support for the forthcoming Euro 7 framework, which introduces limits on particle emissions due to tire wear and will compel manufacturers to improve tire formulations and durability. By synthesizing current knowledge and identifying gaps, the narrative review also guides future research towards safer, more sustainable, and more efficient mobility solutions. Its contribution to sustainability and energy efficiency is equally relevant, as it fosters the development of bio-based and environmentally friendly tire materials and production processes that can reduce rolling resistance, fuel consumption, and greenhouse gas emissions. A reduction of only ten percent in tire wear, for instance, could translate into economic savings of several billion euros by 2050. At the same time, the study emphasizes the need for technological innovation, particularly the advancement of real-time friction coefficient estimation methods and the adaptation of tire technologies to meet the demands of electric and autonomous vehicles, thereby stimulating broader innovation across the automotive industry.

A narrative review paper is essential to synthesize current findings, support regulatory updates (e.g., Euro 7), and guide future research toward safer, greener mobility. A diagram for the tire innovation roadmap from inception to emerging technology is presented in Figure 2.

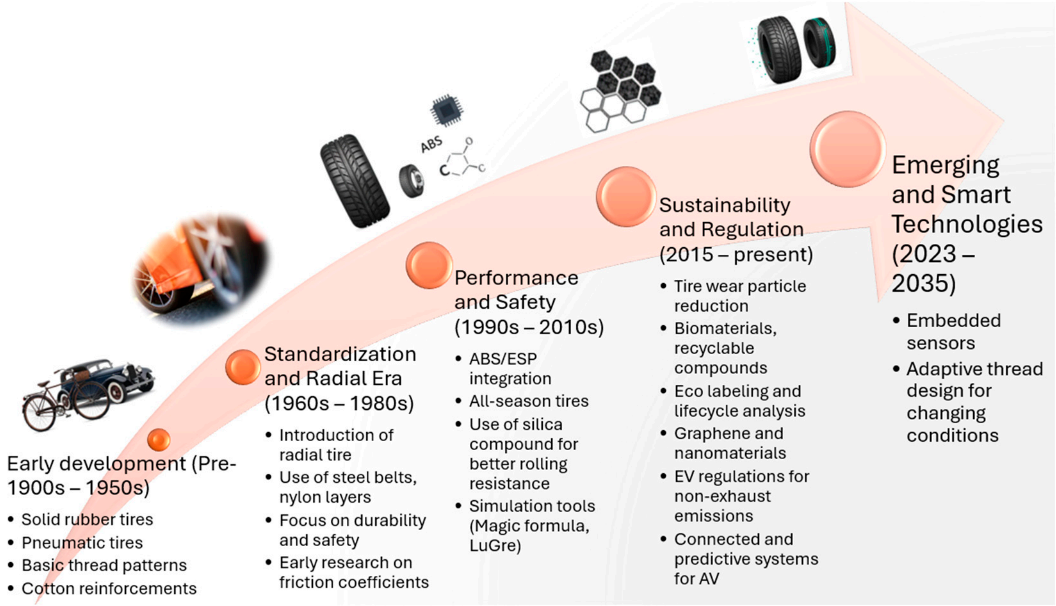


Figure 2. Tire innovation roadmap.

Against this background, the primary objective of the review is to provide an updated and integrated synthesis of the tire–road friction coefficient, to highlight the factors that shape it and the existing models of tire–road interaction, and to delineate the future technological challenges associated with emerging mobility paradigms, sustainability imperatives, and the ongoing digitalization of the automotive sector.

The remainder of this paper is organized as follows: Section 2 provides an overview of the methodological approach, including the search strategy and thematic analysis. Section 3 discusses the results, including the tire–road friction process, factors that affect the coefficient of friction, and tire–road interaction models and methods, while Section 4 explores the effectiveness, challenges, and limitations of the influence of tire–road friction, as well as technological challenges for the future in tire technology. Section 5 presents the final conclusions of the review.

2. Bibliometric and Thematic Methods

This narrative review employed a combined bibliometric and thematic analysis. An extensive search was conducted in Scopus and Web of Science (WoS), both internationally recognized databases, to identify relevant review articles.

Scopus was chosen for this study because of its extensive coverage of both journals and conference proceedings, offering a broad range of academic outputs relevant to the field of tire–road interactions. As highlighted in previous studies [11], Scopus provides comprehensive indexing, which is vital for complete bibliometric analysis. In contrast, the Web of Science database uses a more selective indexing approach, which may restrict the scope of the dataset and exclude valuable sources from more specialized areas.

Thematic analysis was then applied to extract and synthesize key research directions, focusing on factors influencing the tire–road friction coefficient, pavement surface characteristics, tire design, friction mechanisms and models, measurement methods, applications of fuzzy logic and artificial intelligence, laboratory and finite element studies, and implications for electric and autonomous vehicles.

Inclusion criteria:

- Publications related to the automotive sector, such as those mentioned above, including research articles, review papers, conference papers, and books;
- Studies published between 1968 and 2025 to capture the latest trends and advancements;
- Studies published in English.

Exclusion criteria:

- Articles not specifically focused on the key research direction;
- Non-peer-reviewed works and gray literature, excluded to ensure data quality and reliability;
- Papers published in languages other than English, or outside the specified publication window.

The initial bibliometric analysis of scientific publications contains the main keywords in clusters: "vehicle dynamics, tire–road friction coefficient, friction, electric vehicle, road, tire", as can be observed in Figure 3, generated with VOSviewer software, version 1.6.20. The figure was generated using in background a .csv file containing all the references from Scopus and WoS.

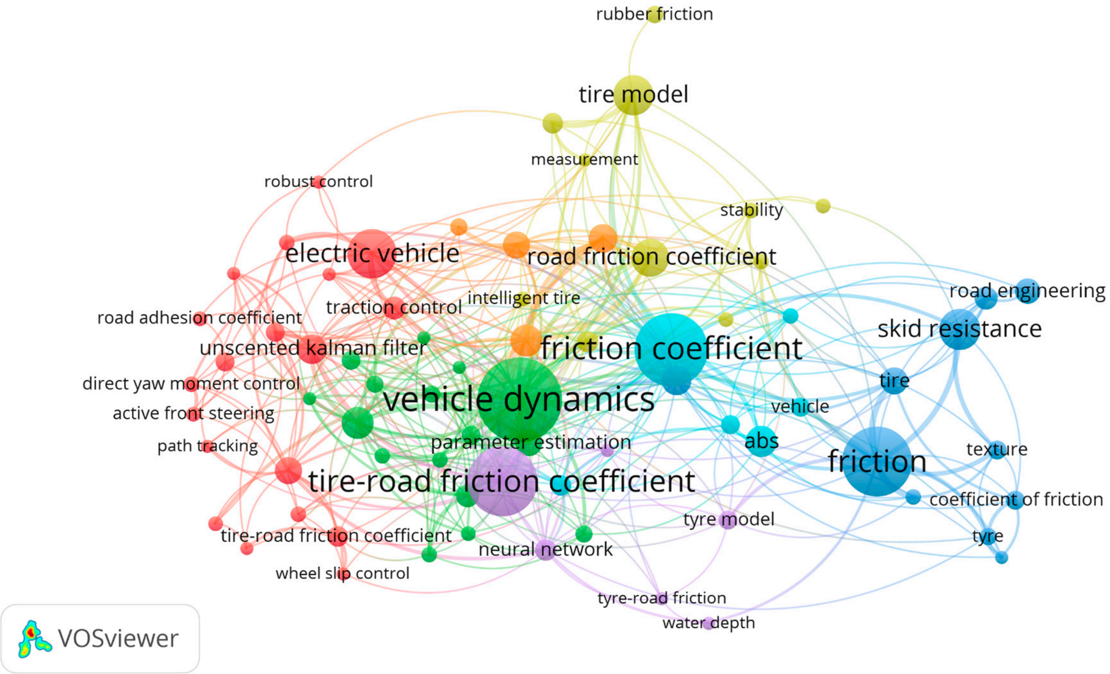


Figure 3. Co-occurrence of authors' keywords.

A search restricted to the keywords "tire", "road", and "friction coefficient" in the Scopus database, covering the period 1968–2025, resulted in the identification of 1362 sources. Among them, 17 are review articles, 529 are conference papers, and 784 are journal articles, while the rest include book chapters, books, errata, notes, and other types. A total of

257 publications are open access. Regarding language distribution, 1216 are in English, 93 are in Chinese, and 12 are in German, with the remaining publications in other languages.

An equivalent search in the ISI Web of Knowledge (Web of Science) for the period 1975–2025 resulted in 966 entries, including 16 reviews, 617 journal articles, 284 conference proceedings, 4 books, and publications in other categories. Among these, 258 are open access. Both databases are internationally recognized and provide exhaustive coverage of the research literature, including works in multiple languages and from various professional associations related to road and vehicle research. In Figure 4 is presented the PRISMA 2020 flow diagram supporting the identification and screening of the selected papers.

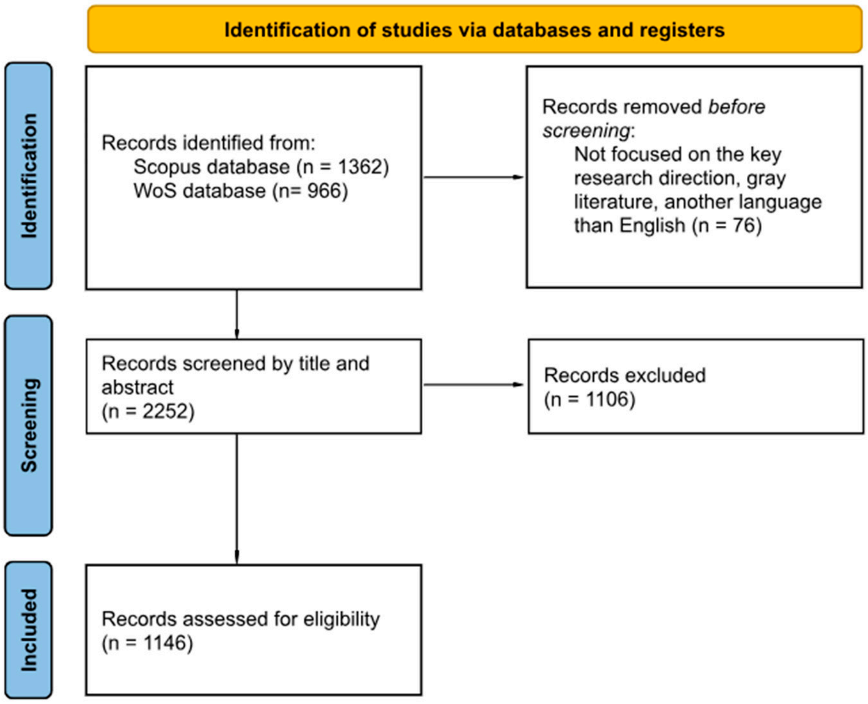


Figure 4. Literature screening process.

For each article, metadata such as the title, authors, affiliations, publication year, journal name, keywords, abstract, and citation count were extracted and organized in an Excel file. This metadata served as the foundation for the subsequent bibliometric analysis. The analysis was carried out independently by both authors, with any discrepancies resolved through discussion and mutual agreement.

The thematic analysis of the review articles highlights the following research directions:

- Key factors affecting the tire–road friction coefficient, such as rubber chemistry, tire pressure, vertical load, temperature, and contact patch size—[4,12–16].
- Pavement surface conditions and composition—[13,14,17–21].
- Tire design and its impact on dynamic behavior—[15,18,19].
- Friction generation mechanisms and tire–road interaction models, including their relevance to vehicle safety systems (e.g., ABS and ESP)—[18,20–35].
- Friction coefficient measurement methods—[22,29].
- Use of fuzzy logic and artificial intelligence in modeling tire–road interaction—[16,29,35–38].
- Laboratory testing studies—[39]; finite element analysis (FEA) approaches—[27].
- Applications tailored to electric and autonomous vehicles—[30,38].

Given the bibliometric analysis conducted, there is a clear need for the development of an updated and integrated review paper that reflects the multidimensional complexity of tire–road interaction in the context of new mobility, sustainability, and digitalization requirements in the automotive industry.

The methodology has certain limitations, such as the potential for selection bias due to the restriction to English-language publications. This decision was made in acknowledgment of English being the primary language of scientific communication, which helps ensure the wider dissemination and accessibility of findings within the global research community. However, this language restriction may have resulted in the exclusion of relevant studies published in other languages, thereby potentially narrowing the cultural and contextual diversity of the evidence base. Furthermore, the review did not include gray literature and did not employ a formal quality assessment of the included studies, which could have impacted the comprehensiveness and reliability of the conclusions drawn.

Review Questions

The review questions were derived directly from the primary objectives of the review, serving as the foundation for structuring the literature search process. They were relevant in shaping the inclusion and exclusion criteria, ensuring that only the most relevant papers were considered for this systematic review.

RQ1: What are the main challenges and potential solutions for reducing tire wear particle (TWP) emissions under the Euro 7 regulations through material innovation and tread design optimization?

The forthcoming Euro 7 regulations place strict limits on non-exhaust particle emissions, with tire wear particles (TWPs) identified as a significant contributor to airborne micro- and nano-particulate pollution. The central challenge for tire developers lies in reconciling environmental objectives, lower TWP generation, and improved material sustainability with performance requirements such as grip, rolling resistance, and durability. The literature reviewed in this study highlights that improving abrasion resistance often increases tread hardness, which can negatively affect wet grip and ride comfort. Conversely, soft, high-traction compounds tend to elevate wear rates and particle release.

RQ2. How do new technology-based methods improve the accuracy and robustness of real-time tire–road friction coefficient estimation compared with traditional model-based approaches?

TRFC estimation methods, based on new technologies such as AI could advance beyond conventional model-based observers by learning complex, nonlinear relationships between tire, vehicle, and environmental variables directly from sensor data. Traditional approaches, such as slip–slope analysis and analytical tire models, depend heavily on accurate physical parameters and well-defined slip conditions. Their performance degrades when environmental factors such as surface wetness, temperature variation, or uneven road textures introduce uncertainties in the tire–road interface. In contrast, AI-driven estimators, including neural networks, support-vector machines, and hybrid data-fusion models, can adaptively infer friction levels from multiple noisy inputs (e.g., wheel speeds, longitudinal/lateral acceleration, torque, and temperature).

3. Results

Tire–road friction has long been recognized as a fundamental factor in vehicle dynamics and safety, with significant research efforts spanning from 1968 to 2025. Over these decades, the understanding of tire–road interaction has evolved dramatically, driven by advances in experimental methods, surface engineering, and computational modeling. Researchers have systematically investigated the key factors influencing the coefficient of friction, including tire tread design, rubber properties, road surface roughness, speed, temperature, and environmental conditions, leading to the development of increasingly sophisticated models. As transportation technology continues to advance, particularly with the integration of autonomous systems, the accurate modeling and optimization of tire–road friction remains the basis for ensuring safety, control, and performance.

Tire tread patterns, shown in Figure 5, are carefully designed to balance performance, safety, and durability. The tread components include ribs, the raised circumferential ridges that provide structural stability; grooves, channels between ribs that evacuate water and reduce hydroplaning; blocks, the individual segments forming the ribs that influence traction and wear; and sipes, thin slits in the blocks that enhance grip on wet or snowy surfaces. Tread patterns come in several types:

- Symmetrical patterns offer a uniform design that balances performance and longevity;
- Asymmetrical patterns combine distinct inner and outer designs, with the outer shoulder enhancing dry grip and cornering stability, while the inner shoulder improves water dispersion;
- Directional patterns, often arrow-shaped, are intended to rotate in a single direction, providing superior water evacuation and traction in snow or mud.

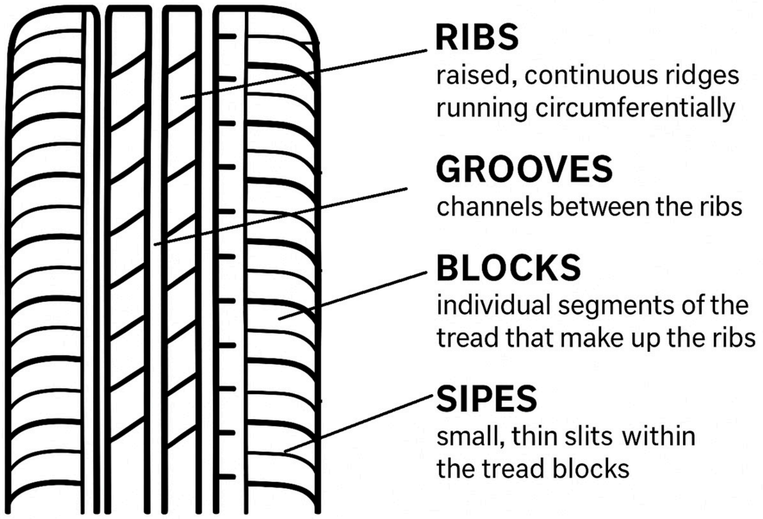


Figure 5. Tire tread pattern design.

Each design choice optimizes tire behavior for specific driving conditions and performance requirements.

3.1. Tire–Road Friction Process

The friction process between the tire and the road can be obtained by cumulating the phenomenon of adhesion friction, where the road surface interacts with molecules from the rubber surfaces due to intermolecular forces, leading to adhesion, with the other phenomenon of hysteresis friction, which represents the energy dissipation due to the viscoelastic deformation of the rubber due to external forces (Figure 6).

On the microscopic and physico-chemical level, the adhesion component of rubber friction arises when a soft rubber tread conforms intimately to a counter-surface (e.g., pavement aggregate) and molecular-scale interactions, primarily van der Waals forces, act across the interface. When rubber chains are brought into proximity with a rough surface, the outermost atoms of the polymer may form weak adhesive bonds with the substrate [40].

As a tire rolls over a road's micro-roughnesses (asperities), the rubber molecules form and break bonds at the contact points. This continuous process generates tangential resistance, which is the force that opposes the tire's movement and is crucial for providing the grip needed for acceleration, braking, and steering.

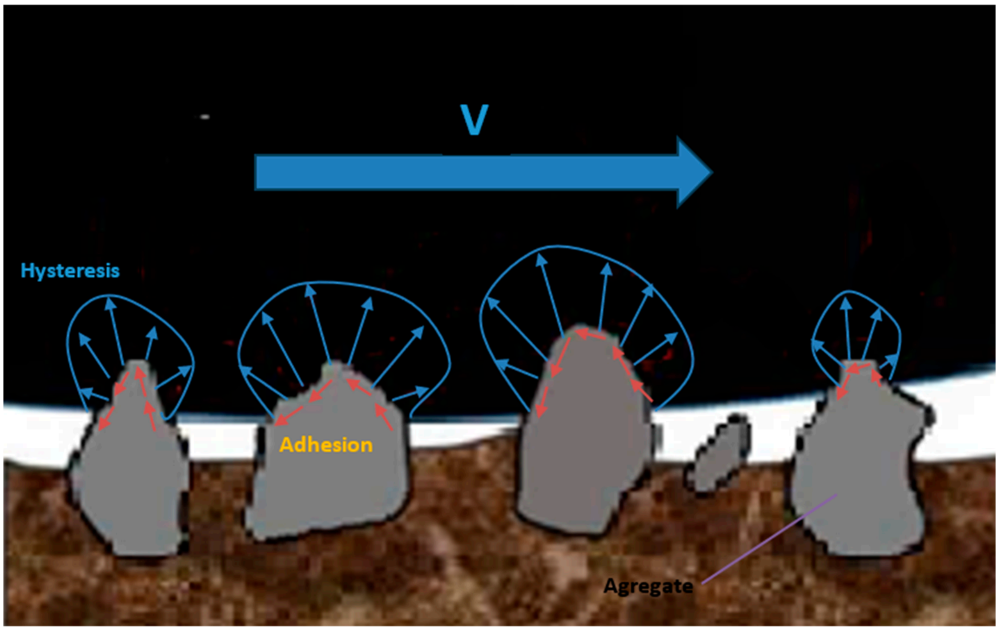


Figure 6. Tire road friction process.

The grip results from molecular bonds between the tire and the road surface, and it is most effective on clean, smooth, dry surfaces. This type of friction is essential for initial adhesion and is very sensitive to contaminants like water, oil, and dirt. Several studies provide insight into adhesion mechanisms, including the behavior of different rubber compounds on wet surfaces. In [41] the authors found a good correlation between adhesive bond energy and friction coefficients. Higher grip allowed higher friction at low speeds, and softer rubber produced higher friction. A method for estimating the maximum tire–road friction coefficient that considers road roughness and texture is presented in [42]. The model incorporates an effective contact patch ratio into the LuGre tire model and characterizes road texture using the road power spectrum. The study in [43] combines field measurements and FEA to analyze tire–road adhesion under various road conditions. A finite element model of aquaplaning was created. The results identified critical water film thicknesses for aquaplaning on different roadways and classified road conditions into dry, wet, lubricated, and stagnant.

Hysteresis is the phenomenon of loss of energy due to the deformation of a tire when it moves on a road. This energy loss generates friction, contributing significantly to grip, especially on rough or uneven surfaces. Hysteresis is the main reason for the appearance of rolling resistance. It involves the dissipation of energy due to the viscoelastic properties of rubber. The energy is lost as heat as the tire deforms over road surface irregularities. This mechanism is particularly important on bad-quality roads, where deformation is more pronounced, enhancing adhesion through energy loss rather than purely adhesive forces.

Hysteresis friction emerges from the viscoelastic nature of rubber: as the tread deforms to fit the road surface, energy is stored and then not fully recovered due to the viscous component of the material's response. This internal dissipation (loss modulus) under cyclic deformation produces a resisting force against relative slide. The viscoelastic behavior of rubber is frequency- and temperature-dependent, so the significance of hysteresis as a friction mechanism depends on contact speed, load, and thermal state. There is a direct relationship: a higher rubber loss modulus (i.e., more viscoelastic energy loss) tends to increase the hysteretic component of friction until competing effects (e.g., excessive softening) reduce shear resistance.

Rubber is a viscoelastic material, meaning it exhibits both elastic and viscous behavior when subjected to deformation. This dual behavior is characterized by the complex modulus, E^*, which is defined as

$$E^* = E' + iE'' \tag{1}$$

where

E' (storage modulus) represents the elastic component of the material's response—the energy stored during deformation and recovered upon unloading. It reflects the stiffness of the rubber and indicates its ability to store mechanical energy;

E'' (loss modulus) represents the viscous component, or the energy dissipated as heat due to internal friction within the rubber′s molecular chains. It characterizes the damping or energy loss behavior of the material.

The ratio of these two moduli is known as tan δ, the loss factor. This parameter is essential in tire and rubber performance because it quantifies the balance between grip (energy loss through hysteresis) and rolling resistance (energy conservation). A higher E'' or tan δ, typically increases hysteretic friction and traction, but also increases energy dissipation and wear.

At low temperatures or high frequencies, rubber behaves more elastically (high E', low E''); at high temperatures or low frequencies, it behaves more viscously. This dependence directly influences tire–road interactions, especially under varying speeds and thermal conditions.

Together, adhesion and hysteresis constitute the dominant mechanisms in rubber-surface friction: adhesion dominates at low speeds and smooth counter-surfaces (where the real contact area is large), while hysteresis becomes increasingly important when deformation over rougher textures and higher speeds occurs.

Research [41,44] highlights how hysteresis affects rolling resistance and vehicle performance. A review in [45] explores the mechanisms of skid resistance for asphalt pavements, examining tire friction, tire–road contact, and influencing factors. It emphasizes the importance of selecting appropriate contact or evaluation models, emphasizing the need for improved accuracy in finite element methods. Key factors for good initial slip resistance include optimized aggregates, asphalt binders, geometric designs, and construction quality. Pavement texture is crucial for skid resistance, especially in wear layer technology. In [46] the authors claimed that initial rolling resistance torque is high due to hysteresis heat generation, which reduces the loss modulus and torsional torque of a tire over time; then, the rolling resistance stabilizes faster at higher speeds and increases with vehicle load. At lower ambient temperatures it is found that the torque is initially affected, with higher initial values, but that it stabilizes over time. The authors of [47] developed a comprehensive model for predicting the rolling resistance force of tires to improve vehicle energy efficiency and comply with environmental regulations. Using FEA of visco-hyperelastic tires, the study validates simulations with test data and derives a formula to predict rolling resistance based on speed, inflation pressure, and load. In [48] the authors explored the friction properties of a tire tread compound on asphalt road surfaces. This involved measuring power spectra of surface roughness and friction at various speeds and temperatures. The results indicated that, at low speeds, the friction due to the actual contact area—driven by the shearing of a thin film of rubber smear—was particularly significant on the smooth road surface analyzed. Understanding and optimizing tire–road friction is critical to developing tires that balance grip, durability, and environmental impact while meeting current driving demands.

A tire adapts to the texture and irregularities of a road surface by deformation of the tire tread, improving friction and grip through mechanical interlocking between the tread and the road. Such interlocking is particularly effective on rough or textured surfaces and plays a crucial role in providing traction on loose or uneven terrain. Research using finite element analysis (FEA) explores how tire deformation affects ground contact characteristics, rolling resistance, and traction performance on different surfaces. The way in which the dimensions of pavement aggregates influence tire–road contact was analyzed using FEA in [49]. Thus, wheel–road interaction was analyzed under steady-state driving and braking conditions for different sizes of aggregates. The authors mention that the maximum contact stress increases with the depth of the pavement texture, while the contact area decreases. The study also introduces the concept of occlusal depth to evaluate pavement skid resistance and found no clear correlation between aggregate size and tire–pavement contact interaction. A technology based on pressure-sensitive film was used in [50] to study the tire–road contact characteristics on different asphalt pavements. The research shows that tire contact patches are influenced more by load than inflation pressure. The authors found that increased pavement texture depth decreases the contact area, and the peak stress at the tire–road contact can significantly exceed design loads, providing information on tire design and pavement performance. In [51] the authors developed an FEA model to explore the conflict between tire rolling resistance and grip performance. Their simulations show that the longitudinal tensile deformation of the tread affects both rolling resistance and grip. By increasing longitudinal tensile stress, grip is improved, but rolling resistance is also increased, highlighting the trade-off between these two performance values. The study also suggests that optimizing cross-groove patterns can improve both rolling resistance and grip performance. Some books such as *Tire and Vehicle Dynamics* by Hans Pacejka provide comprehensive coverage of tire mechanics and friction [52]. *The Science and Technology of Rubber*, Fourth Edition, edited by Mark, Erman, and Eirich, discusses the properties of rubber and their impact on friction [53]. A brush model used in [54] examines how environmental conditions affect road friction characteristics to highlight significant friction differences between wet and dry surfaces, highlighting the importance of pavement conditions for road safety.

The friction coefficient between a wheel and a road is divided into two types:

- The coefficient of static friction is the friction force that must be overcome to be able to determine the movement of the wheel from rest. This is usually greater than the coefficient of dynamic friction. Some references reviewed in this article are [55–58]. A semi-analytical model presented in [57] predicts the normal force distribution, while a beam–spring network captures the friction force and rubber deformation during stick-to-slip transitions.
- The dynamic friction coefficient represents the friction force that acts when a wheel slides on a surface [55,57]. In [59] a hybrid physical–dynamic tire–road friction model is presented for the simulation and control of vehicle motion, extending the LuGre dynamic friction model by incorporating a stick–slip partition based on the physical model of the contact patch.

Typical values for the coefficient of friction for different road conditions are taken from [60,61] and are presented in Table 1. These values are approximate and can vary based on specific conditions and materials.

Table 1. Typical values for the coefficient of friction for different road conditions. Source [60,61].

Road	Static Friction Coefficient, μ_0	Dynamic Friction Coefficient, μ
Asphalt and concrete (dry)	0.8–1.0	0.75
Asphalt (wet)	0.5–0.7	0.45–0.6
Concrete (wet)	0.8	0.7
Gravel	0.6	0.55
Snow	0.2	0.15
Ice	0.1	0.07

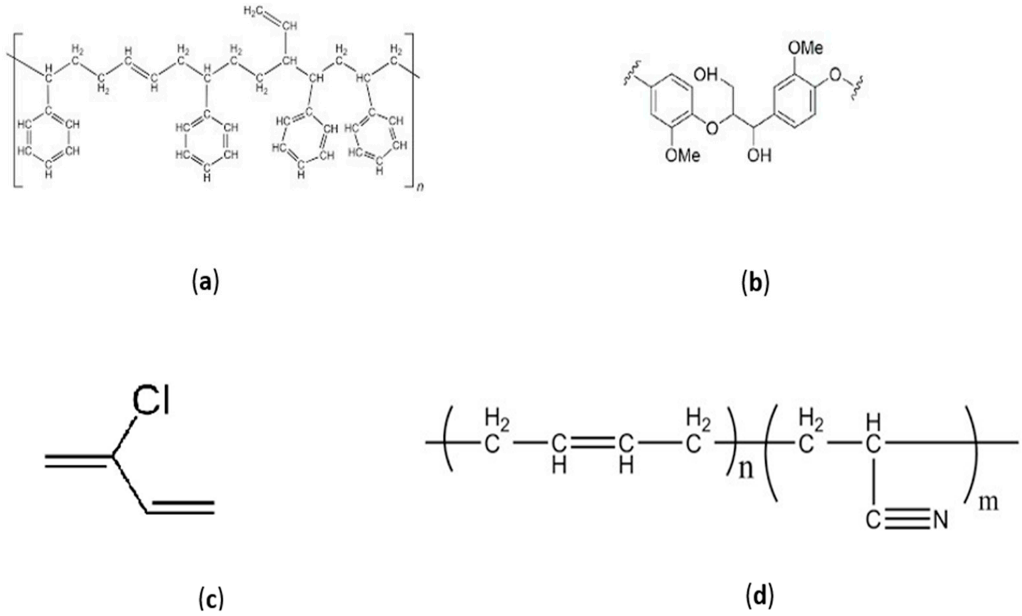
3.2. Factors That Affect the Coefficient of Friction

3.2.1. Tire Composition and Construction

The different materials used in the construction of tires have different friction characteristics. Tires are made from a mixture of natural and synthetic rubber, each with different properties. Natural rubber provides excellent grip due to its high elasticity, while synthetic rubber such as styrene-butadiene rubber (SBR) provides durability and wear resistance. The inclusion of additives such as silicon and carbon black modifies the grip properties of tires to a greater extent. A tire's composition, tread design, and road conditions significantly affect its coefficient of friction with a road surface. A review of how tire composition influences the coefficient of friction is presented below.

Natural rubber (NR) offers tire elasticity and good adhesion, but it does not offer durability, so it wears out faster. The friction coefficient of tires is influenced by the addition of natural rubber, due to its high elasticity, resistance, good grip on wet ground, and low heat accumulation. These properties contribute to good tire traction and handling in various conditions [62]. Tread compounds with a high percentage of natural rubber usually have better traction and grip, especially in wet conditions. Tire manufacturers blend natural rubber with synthetic rubber and other additives to optimize performance characteristics [63], wear resistance, and rolling resistance, without compromising the friction coefficient. Different types of tires (e.g., high-performance, summer, winter, and all-season) have different proportions of natural rubber in their composition to achieve the desired performance results. By using natural rubber exclusively as the tire tread material, a higher concentration of 5–10 μm tire wear particles results. By mixing natural rubber with butadiene rubber in the tread component, the concentration of tire wear particles decreased. Changing the type of carbon black also reduced the amount of tire wear particles in the 2.5 μm size range [10].

Synthetic rubbers are artificial elastomers which are obtained from petroleum products and have diverse properties and applications in tire manufacturing. Styrene-butadiene rubber (SBR) offers balanced performance and grip, butadiene rubber (BR) enhances resilience and efficiency, chloroprene rubber (CR) excels in harsh environments, and nitrile rubber (NBR) provides specialized chemical resistance with moderate friction (Figure 7).



(a) (b) (c) (d)

Figure 7. Synthetic rubber type, chemical structure, in tire construction: (**a**) SBR; (**b**) BR; (**c**) CR; (**d**) NBR.

By adjusting the composition of the polymers and additives in the synthetic rubber, the coefficient of friction can be changed. Combining synthetic rubber with natural rubber or other compounds can improve dry grip while balancing other performance factors such as durability and rolling resistance [63]. Synthetic rubber, like styrene-butadiene rubber, gives a tire superior wet grip due to its ability to maintain flexibility and grip. The synthetic rubber in the tread structure, along with its design, can improve water evacuation from the tire surface, reducing hydroplaning and maintaining contact with the road. Synthetic rubbers usually provide better performance at high temperatures compared to natural rubber. This reduces the risk of degradation due to heat and maintains the friction coefficient with the road, due to the synthetic rubber used. Winter tires remain flexible at low temperatures, ensuring a high coefficient of friction in cold conditions. Compounds used for tread construction often consist of a blend of synthetic and natural rubber to optimize adhesion, wear resistance, and rolling resistance and provide excellent air retention, maintaining proper tire pressure and increasing safety [62]. The tires have low permeability, so they stay inflated for longer periods of time. Adjusting the ratio of synthetic to natural rubber, together with specific additives, leads to the achievement of desired performance characteristics for different types of tires. Synthetic rubbers used in the structure of the sidewall tire layers increase durability and resistance to environmental stressors, contributing to the integrity of the tire. The sidewalls are designed to balance strength and flexibility, ensuring that the tire can withstand impacts and maintain performance over time. In [64], it is mentioned that the same rubber compounds and treads may not always provide optimal performance for tires of various constructive types (e.g., radial and cross-ply), but it is considered of interest and importance to compare the relative performance of several typical tread compounds on various types of tires.

Silica added to the tire component improves the adhesion between the tire and the road surface in wet conditions by reducing the water film and offering better traction and shorter stopping distances on wet surfaces [63]. Tires with silica maintain the flexibility of the rubber compound at lower temperatures, which is essential for maintaining wheel grip during cold weather when roads are icy. This ensures safety during the winter. When a tire deforms during contact with a road, silica reduces energy loss, thereby reducing rolling resistance [62]. This leads to efficiency and fuel economy, without significantly compromising the grip needed to provide wheel traction. Added to the rubber compound, silica offers better resistance to wear, extending the life of the tire, thus ensuring the tire's long-term performance. Some research found that organoclay [65] enhances silica coupling and improves traction on wet road and rolling resistance, while carbon black addition results in lower dispersion and no improvement in dynamic properties. Modified natural rubber with silica reinforcements [66] improves compatibility and reduces protein interference, advancing silica technology for natural rubber in tire compounds. High-dispersion silica is favored over carbon black for low-rolling resistance tires, despite challenges with natural rubber combinations.

The impact of carbon black on the mechanical and frictional properties of tire treads is analyzed in [67]. Tire rubber compounds contain carbon black, which improves tires' wear resistance, heat dissipation, coefficient of friction, and general performance. It is an essential component of several types of tires, including high-performance and regular passenger tires, due to its ability to increase dry traction and durability. Recent studies investigated the possibility of using, by pyrolysis, the carbon black from used tires as a carbon carrier for metals (Co, Ni, Cu, and Fe) and their oxides to produce catalytic systems [68].

Plasticizers enhance tire flexibility and grip, especially in cold conditions, by making rubber more pliable. Resins increase traction by improving rubber stickiness, particularly in wet conditions. Antioxidants and anti-ozonants protect tires from environmental degradation, maintaining performance over time. Sulfur (Figure 8) and accelerators enhance rubber curing, improving durability and traction across all tire types.

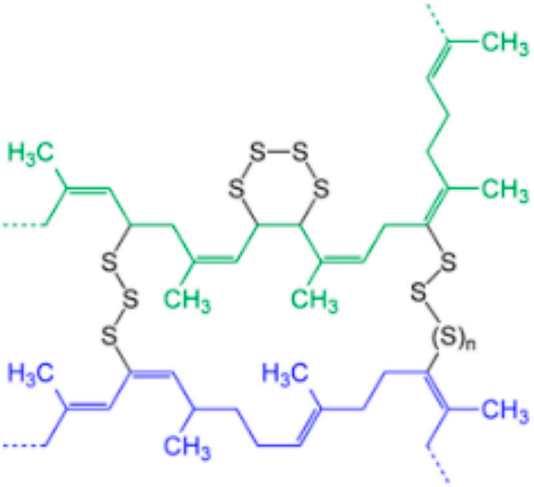


Figure 8. Sulfur vulcanization: chemical structure of vulcanized natural rubber.

In [69] the authors study the effect of sulfur vulcanization systems, i.e., conventional vulcanization (CV) and efficient vulcanization (EV), on the mechanical properties and thermal aging resistance of natural rubber with reclaimed rubber blends used in tire tread construction. Mechanical properties such as tensile properties, tear strength, and abrasion resistance are determined. The results show that the blends made with both vulcanization systems show an increase in their pain and modulus with increasing recovered rubber content, while other mechanical properties are negatively affected. In addition, most of the mechanical properties of conventionally vulcanized products are generally higher than those obtained by effective vulcanization. It also appears that the tensile strength and tear strength of CV and EV vulcanized products become comparable when the recovered rubber content is this high.

The pattern and depth of the tread influence the coefficient of friction between tire and road. Aggressive patterns with deep grooves enhance traction on loose surfaces such as mud or snow, whereas smoother patterns are optimized for dry conditions. The small slits in tread blocks improve adhesion on wet and icy surfaces by creating more biting edges. Deeper treads provide better water evacuation and grip on wet surfaces, but may increase rolling resistance. A method and formula to determine road friction coefficients using strains on a tire sidewall are proposed in [70], despite the fact than many studies have been conducted to measure road friction coefficients using strains at the inside surface of a tire tread. Sensors installed on the inside surface of a tire tread, where significant deformation occurs locally because of protrusions on road surfaces, can easily be peeled off or damaged.

3.2.2. Road Surface

The road surface significantly impacts the tire–road friction coefficient. The interaction between tires and various road surfaces is analyzed in [55], including the impact on friction. Road surface materials and their influence on vehicle performance and safety are discussed in [71]. Factors like material composition, texture, surface conditions, and temperature play important roles. Asphalt and concrete offer good friction, but their effectiveness varies with wear and texture. Surface macro-texture enhances grip, while micro-texture affects adhesion at the microscopic level. Wet conditions, icy roads, and contaminants reduce friction, increasing the slippage risks. Many examples highlight differences in friction between new and worn surfaces [72–74] and between various road materials under different conditions. In [72] the focus is on reducing energy consumption due to tire–road interaction by the selection of pavements with lower rolling resistance—and hence lowering CO_2 emissions and increasing energy efficiency.

A lower contact area and steeper slopes of the mineral aggregate edges cause local strains and deformations to be very high. Due to the hysteresis of the tread material and the nonlinear phenomena typical of it, the increase in deformation leads to substantial increases in energy losses, which result in increased rolling resistance (Figure 9) [74].

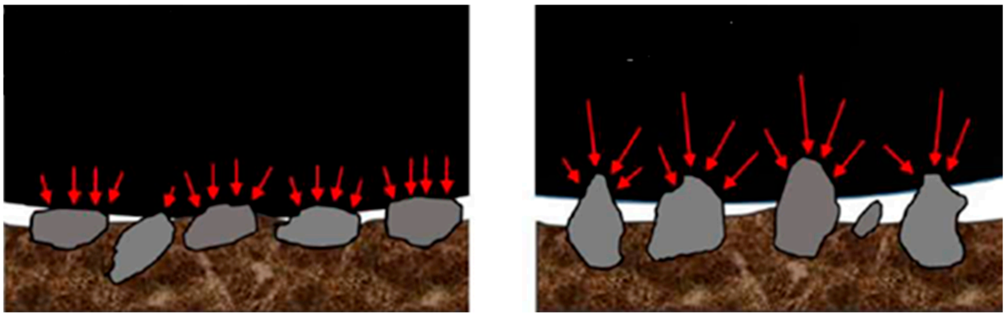


Figure 9. The tire deformation for different pavement structures generates different hysteresis of material [74].

The test method presented in ASTM E274/E274M-15 [75] establishes the standard procedure for measuring the skid resistance of paved surfaces using a specified full-scale automotive tire. A prediction model representing the braking process of a vehicle, correlating the tire–road friction at the optimum design slip speed with the macro-texture and micro-texture of pavement, is established in [76] using a multivariate nonlinear regression analysis.

3.2.3. Temperature

Road and ambient temperatures affect the coefficient of friction between tires and road surfaces. Fluctuations in temperature also influence the friction between wheel and road. Given these considerations, it can be said that heat improves grip and generates a softer tire rubber, while cold can harden it. Different tire compositions are optimized for specific weather conditions, e.g., summer tires are optimized for high temperatures and winter tires for cold weather. Road surfaces also react to temperature changes. Asphalt can become soft when exposed to heat, improving wheel traction, while a layer of ice and snow can significantly reduce friction in cold weather conditions. Concrete is less affected by temperature changes compared to asphalt, but it can still expand and contract, affecting its texture and, therefore, friction levels. On highways, where higher speed regimes are in place and the traffic is more consistent, heat can be better retained than on urban roads, influencing friction levels differently. Seasonal tire performance varies significantly, with inappropriate tire usage leading to safety risks. The ambient temperature, according to [77], has an influence on the particle emissions resulting from tire wear during driving. Thus, a low temperature seems to be favorable for summer tires and a higher one seems to be favorable for winter tires. A higher temperature of the pavement, of the ambient environment, and of the air in the tire led to a lower hysteretic friction for a certain surface of the pavement and a certain slip ratio of the tire. Conversely, a lower tire slip ratio and a more highly macro-textured pavement resulted in higher friction. A large variation in hysteretic friction shows that a critical combination of factors can reduce the level of friction significantly [78]. The influence of the temperature of the tire in its core and/or on its surface, on its stiffness in turns, and the coefficient of lateral friction is analyzed in [79].

3.2.4. Tire Load and Pressure

Load tires, inflation pressure, and wheel speed have effects on the rolling resistance and grip of automobile tires [80]. The wheel–road interaction in the contact patch is studied in [81,82], considering the wheel load and inflation pressure. The results of [50] showed that contact pressure is uneven in the contact patch and lower than air pressure for the radial tire, but in some cases higher for bias-ply tires in dual configuration. In [82] it is said that in most road design methods, it is assumed that the compressive stress at the tire–road contact is equal to the inflation pressure of the tire and is uniformly distributed over a circular area. The tensile strains in the asphalt layer under actual contact stress, however, are quite different from those under uniform constant stress. The weight on the wheel can alter the contact patch and thus the friction. Increasing the load on a tire generally enhances the contact area, which can enhance friction but in a nonlinear way. However, excessive load can lead to over-deformation and reduced performance. Proper inflation maintains the optimal contact patch. Under-inflated tires increase rolling resistance and wear, while over-inflated tires reduce the contact area, leading to less grip. Proper pressure distribution under increased load optimizes friction, while excessive load causes uneven pressure and reduced friction. Load-induced tire deformation improves grip to a point but can increase slip angles, affecting handling. Heat generation from higher loads also alters rubber properties. Overall, maintaining an optimal load is essential for maximizing tire performance, as both underloading and overloading can reduce friction and safety. Particle emissions generated by tire wear increase disproportionately with the force applied to the wheel in the longitudinal and lateral direction [77]. Winter tires generated the highest emissions at all loads, and summer tires resulted in the lowest. Lateral forces caused much higher emissions than longitudinal forces. With an increase in load and wheel speed there is an increase in rolling resistance and tire temperature. Also, the rolling resistance and tire temperature increases with decreasing inflation pressure. The results of an experimental analysis in which inflation pressure, load, and speed were varied show that the tire with nitrogen gas resulted in lower rolling resistance and a lower tire temperature as compared with air [83]. The results of the experimental study in [84], which covered a wide range of different wheel loads and inflation pressures for different tires, show the significant influence of inflation pressure on longitudinal tire characteristics such as slip stiffness and maximum traction force. Also, an extended HSRI tire model shows good model accuracy in representing the influence of inflation pressure upon tire characteristics.

3.2.5. New Tire Production Technology

A large percentage of automotive product pollution comes from the production of tires and their end use. From this perspective, the production of tires using eco-friendly materials and technologies that present minimal danger to the environment is a current topic of research [85].

Tires have a significant impact on the energy consumption of motor vehicles. Increasing their energy efficiency can reduce fuel consumption by up to 5%, thus saving 30 billion liters of fuel annually and reducing greenhouse gas emissions by over 100 million metric tons [86]. The new generation of tires focus on reducing rolling resistance and maintaining proper inflation, which increases durability and efficiency and reduces environmental impact. Technological advances in tire production, including the use of sustainable materials, aim to reduce the reliance on oil in tire production, reducing the carbon footprint of related industries.

Michelin aims for all its tires to be made entirely from sustainable materials by 2050, up from the current 28 percent. To achieve this, the company plans to enhance research and form partnerships for bio-sourced butadiene and work on recycled polystyrene. Michelin is also building its first tire recycling plant [87]. The Bridgestone company has introduced a new technology which combines chemically optimized synthetic rubber with tailor-made silica to create tires with up to 30% better wear efficiency and a rolling resistance that is reduced by up to 6%, enhancing tire lifespan and reducing environmental impact through improved wear efficiency and fuel consumption. Both companies emphasize innovation and collaboration as central to their sustainability strategies [87].

The processes of sustainable tire manufacturing develop year after year, using ecological materials and the improvement of production technologies. Innovations include alternatives to natural rubber, such as guayule and dandelion rubber, and the use of recycled materials, such as polyester from plastic bottles. Sustainable sources of silica, such as rice husks, also reduce environmental impact. Green manufacturing practices focus on energy efficiency, low emissions, and waste reduction. Green tires offer benefits such as reduced environmental impact, fuel efficiency, good performance, and longer lifespan. Future developments include smart tires with advanced sensors and biodegradable tires, moving the industry towards a circular economy [88].

As sales of electric vehicles increase, estimated to reach almost 25% of total sales in 2030, the tire industry must focus on developing specific tires to support this transition to sustainable mobility. Electric vehicles require special tires for supporting the increased weight, the possibility of transmitting increased traction force, and the generation of reduced noise from the road. From this point of view, electric vehicle tires differ from those of traditional vehicles. To support the greater mass of electric vehicles, tires are built to handle 10–20% more weight, ensuring durability and optimal performance [89]. Low rolling resistance, which increases battery efficiency, is achieved through specific rubber compounds and designs. Strong initial acceleration and high torque are ensured by stiff and wide center rib patterns and locking grooves. Durability and power delivery are achieved using advanced compounds, including highly charged resin and silica. Noise reduction is achieved by tires designed to minimize road noise through specialized tread patterns and sound-absorbing materials.

3.3. Tire–Road Interactions Models and Methods

Tire–road interaction models enable the estimation of longitudinal and lateral forces, simulation of vehicle dynamics, and evaluation of the influence of terrain (asphalt, mud, and snow) on traction. Some of these models are employed for the virtual testing of tread patterns, contributing to time and cost savings during the prototyping phases.

Various classifications of existing models can be made according to different criteria.

A review [90] categorizes the models into semi-empirical models, finite element models, and experimental models, providing a critical analysis of each. Another classification, according to [91], distinguishing driving dynamics models and comfort models, constitutes an alternative perspective.

Based on our bibliometric analysis, and in response to the objective of “developing a classification of tire–road interaction models,” we identify three main categories: Empirical (or Semi-Empirical) Models, Analytical/Physical Models, and Data-Driven/Numerical Models.

In the present study, we will consider as representative those models that appear most frequently in the bibliographic references indexed in Web of Science and Scopus, analyzed during the course of this research. Thus, by querying these databases with the keywords “Magic Formula,” “Brush,” “Dugoff,” “Burckhardt,” “LuGre,” “Fiala,” “FEA,” and “FEM,” we obtained the number of publications addressing the topics related to the models listed in Table 2. This table provides an overview of the characteristics and application domains of these models, along with selected bibliographic references. The brush model and the Fiala model are closely related; in fact, the Fiala model can be seen as a specialized, closed-form version of the brush model. That is why many sources present them as "the same formula" or at least mathematically equivalent under certain assumptions. Fiala applied simplifying assumptions to the brush model: uniform pressure distribution; linear bristle stiffness in shear; symmetry in the contact patch. With those assumptions, he derived explicit equations for lateral force vs. slip angle. Because of that, many books and papers present Fiala's equations when researching the brush model, since Fiala gives you a ready-to-use formula instead of requiring numerical integration.

Table 2. Summary of tire–road interaction models, their characteristics, and application domains.

Model	Characteristics	Typical Applications	Mathematical Description	No. of Papers in WoS	No. of Papers in Scopus	References
Magic Formula (Pacejka)	High accuracy; fits real data well; works for lateral, longitudinal, and combined slip	Vehicle dynamics, handling studies	Lateral force: $Fy(\propto) =$ $Dsin\{C{\cdot}arctan[B \propto -E(B \propto -arctanarctan\ (B \propto)\ )]\}$ where α—slip angle (rad) B—stiffness factor (slope near origin) C—shape factor D—peak factor (max force) E—curvature factor (asymmetry in curve) Extended versions include combined slip, camber, and longitudinal force.	34	45	[92–96]
Dugoff Model	Simple, computationally light, analytical form	Control design (ESC, path tracking); simplified dynamics	Longitudinal and lateral forces: $Fx = Cs{\cdot}\frac{s}{1+s}{\cdot}f(\lambda)$ $Fy = C\alpha\frac{tantan\ (\alpha)}{1+s}{\cdot}f(\lambda)$ $f(\lambda) = \begin{cases} (2-\lambda)\lambda\ ,\ \lambda < 1 \\ 1\ ,\ \lambda \geq 1 \end{cases}$ $\lambda = \frac{\mu Fz(1+s)}{2\sqrt{(Cs{\cdot}s)^2 + (C\propto{\cdot}tantan\ (\alpha)\ )^2}}$ where F_x, F_y—longitudinal and lateral forces s—longitudinal slip ratio α—sideslip angle C_s, C_α—longitudinal and lateral stiffness of tire μ—friction coefficient F_z—normal tire force λ—adhesion utilization factor $f(\lambda)$–saturation function	31	36	[97–101]
Brush Model	Good physical insight, handles combined slip, moderate complexity	Teaching. theoretical studies; control-oriented model	Lateral force: $Fy =$ $\begin{cases} 3\mu Fz\theta y\sigma y\left[1 - \lvert\theta y\sigma y\rvert + \frac{1}{3}(\theta y\sigma y)^2\right], \lvert\alpha\rvert \leq \alpha sl \\ \mu Fz{\cdot}sgn(\alpha), \lvert\alpha\rvert > \alpha sl \end{cases}$ $\theta y = \frac{2Cpya^2}{3\mu Fz}$ $tan\tan(\alpha sl) = \frac{1}{\theta y}$ where a—half the contact length C_{py}—lateral stiffness θy—tire model parameter $\sigma_y = \tan(\alpha)$—slip α—slip angle F_z—vertical load M—friction coefficient	18	47	[52,102–106]
LuGre Model and variants	Captures transient effects; can model stick–slip and hysteresis phenomena	Vehicle dynamics simulation; vehicle control design	Friction force: $F = \sigma 0{\cdot}z + \sigma 1{\cdot}\dot{z} + \sigma 2{\cdot}v$ $\dot{z} = v - \frac{\lvert v\rvert}{g(v)}z$ $g(v) = \mu c + (\mu s - \mu c){\cdot}e^{-\lvert\frac{v}{vs}\rvert^{\frac{1}{2}}}$ where z—internal bristle deflection v—relative velocity (slip speed) σ_0—stiffness coefficient [N/m] σ_1—damping coefficient [Ns/m] σ_2—viscous friction coefficient [Ns/m] μ_s, μ_c—static and Coulomb friction coefficients v_s—Stribeck velocity	24	24	[106–112]
Burckhardt Model	Less complex model than some others	Suitable for ABS/TCS, friction estimation, braking studies	Longitudinal force: $Fx = \mu(k){\cdot}Fz$ $\mu(k) = a1{\cdot}(1 - e^{-a2k}) - a3k$ where K—slip ratio Fz—normal tire force a_1, a_2, a_3—fitting parameters	11	13	[110,113–115]

Table 2. *Cont.*

Model	Characteristics	Typical Applications	Mathematical Description	No. of Papers in WoS	No. of Papers in Scopus	References
Fiala Model Stretched String	Less accurate for combined slip (braking + cornering); does not capture road condition changes	Suitable for preliminary vehicle simulations; does not provide sufficient accuracy for complex vehicle handling scenarios	Lateral force: $Fy =$ $\begin{cases} -C\alpha \cdot tan(\alpha)\left(1 - \frac{\lvert C\alpha \cdot ta(\alpha)\ \rvert}{3\mu Fz} + \frac{(C\alpha \cdot ta(\alpha)\ )^2}{27\mu Fz^2}\right), \lvert\alpha\rvert \leq \alpha sl \\ -\mu Fz \cdot sgn(\alpha),\ \lvert\alpha\rvert > \alpha sl \end{cases}$ Slip angle limit: asl = arctan($3\mu F_z/C_\alpha$) where α—slip angle C_α—cornering stiffness F_z—vertical load μ—friction coefficient	5	5	[52,116,117]
FEM Models	High fidelity, detailed deformation and contact patch	Tire design, material research, structural analysis		2	5	[118–120]

As a common element of all models, we have included a general diagram of the wheel, which illustrates the forces and moments acting on it (Figure 10).

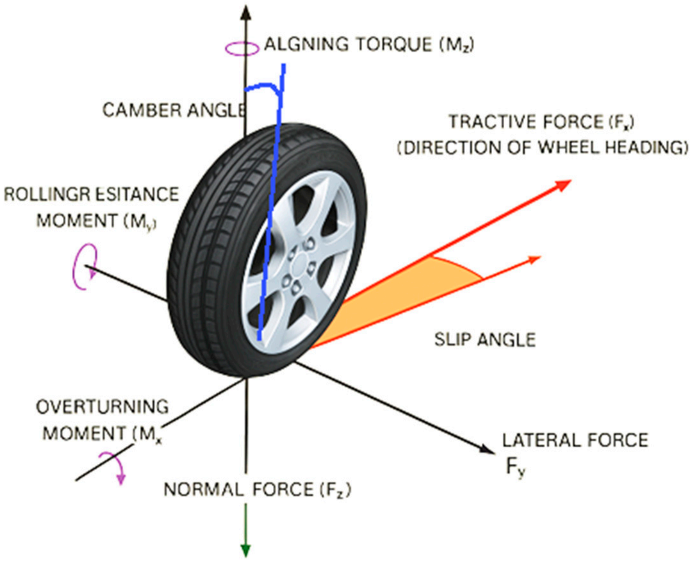


Figure 10. Axis system, forces, and moments acting on wheel models.

The Magic Formula model [92–96] remains a benchmark for lateral and longitudinal force prediction in many simulation applications. Both the Magic Formula and its extended version, such as the SWIFT model [121], are widely used in the automotive and motorsport industries due to their accuracy and computational efficiency.

Although there is no explicit TRFC in the formulation, the effect of friction is still present implicitly, particularly through the peak factor, D, which scales with the product of the effective friction coefficient and vertical load. In this way, the Magic Formula embeds frictional effects in its fitting parameters rather than introducing them as standalone constants [122]. Pacejka tire models require tire testing for each tire considered. The coefficients do not have physical significance; they are essentially curve-fitting parameters. These coefficients are not readily available; the manufacturers provide raw data showing the forces and aligning moments as a function of slip angle, but the models have high accuracy.

Models based on the LuGre framework [106], along with their flexible extensions and brush-type variants [106–109], are preferred for advanced control applications (ABS and ESC) and for complex transient simulations. The LuGre model characterizes friction through parameters describing bristle stiffness, damping, and viscous effects (σ_0, σ_1, and

σ_2), along with static friction (μ_s), Coulomb friction (μ_c), and the Stribeck velocity (v_s), which together capture how friction evolves from rest to steady sliding. Unlike simple models where TRFC is a single constant friction coefficient, in LuGre it corresponds most closely to Coulomb friction but is enriched by static friction, Stribek velocity, and the dynamic terms, making the model far more realistic than a constant TRFC. So instead of a single constant TRFC, the LuGre model effectively generalizes TRFC into a set of parameters that define how friction evolves with velocity and dynamics. The core value of the LuGre model lies in its ability to describe the dynamic evolution of friction (including pre-sliding displacement and Stribeck effects), rather than providing a single static friction coefficient. This highlights its importance for accurate tire–road interaction modeling and control system design.

The Dugoff tire model [97] is a semi-empirical model widely used in vehicle dynamics for representing tire–road interaction, particularly in longitudinal and lateral slip conditions. It accounts for both longitudinal and lateral forces under combined slip conditions. It is useful for realistic simulation of tire forces during maneuvers like braking while turning. The Dugoff model assumes a rigid wheel and constant vertical load, and the contact patch is modeled with a linear distribution of shear stresses until saturation. The model estimates tire forces as a function of slip ratio, slip angle, vertical load, and tire–road friction coefficient.

The classical stretched string (Fiala) [116] and brush [102] models remain useful for fundamental studies and quick verifications. Advanced models can predict tire wear as a function of load, pressure, and road conditions; estimate particulate matter (PM) emissions from abrasion (tire and road); and contribute to lifecycle analysis and sustainability assessments.

FTire (Flexible Structure Tire Model) [123] is a high-fidelity, physics-based 3D tire model handling in-plane/out-of-plane dynamics, rolling resistance, structural vibrations, and thermo-mechanical effects and is suitable for real-time vehicle simulations and standalone FEA. FTire offers comprehensive realism, including thermal effects and wear modeling, but at a high computational cost.

The FTire model does not rely on a fixed friction coefficient but instead defines friction as a function of sliding velocity, normal pressure, and (optionally) temperature, allowing it to capture effects such as load sensitivity and thermal degradation; consequently, there is no constant TRFC hard-coded in FTire, and the model derives effective friction dynamically through state-dependent characteristics, making it more realistic than simpler models. Reference [124] states that “The rubber temperature of the tread, in addition to the ground pressure and sliding velocity, are used to determine the friction coefficient between the tread blocks and the road.”

The FTire model represents one of the most advanced physically based tire models currently available for vehicle dynamics simulation. Unlike conventional rigid-ring or semi-empirical formulations, FTire explicitly accounts for the dynamic behavior of individual tread blocks and their local contact interactions with a road surface. This detailed treatment allows it to accurately simulate the effects of high-frequency excitations, uneven road profiles, and transient vibration phenomena, which are often challenging for simplified models to reproduce. Consequently, FTire is particularly well-suited for studies involving ride comfort, noise and vibration, and road roughness sensitivity analyses.

High-fidelity finite element (FE) models are ideal for predicting wear and thermo-mechanical effects; however, they are resource-intensive in terms of both software and hardware requirements. Pam-Crash with Mooney–Rivlin rubber [118] is an FEA-based simulation model for truck tires that incorporates thermo-mechanical contact, Mooney–Rivlin rubber behavior, and explicit dynamic analysis. It is applied to study cornering forces, the effects of inflation pressure, and self-aligning torque.

The 3D Finite Element Method (FEM) implemented in ABAQUS provides a high-resolution simulation framework for tire behavior, incorporating static inflation and explicit dynamic analysis under conditions such as pothole impacts and uneven surfaces. The model is validated against laboratory tests and is employed to evaluate transient responses, assess tire durability, and predict chassis loads [119].

Finite element (FE) modeling has become a vital tool in tire engineering, enabling the optimization of tire design, enhancement of vehicle safety, and improvement of overall performance. Key aspects of tire FE modeling include accurate material representation, where tire rubber is commonly modeled using hyperelastic formulations, such as Mooney–Rivlin [125] or Ogden–Roxburgh formulations, to capture its nonlinear, time-dependent behavior, and the detailed modeling of structural components, including tread, sidewall, belt, and bead regions, using solid, beam, or rigid elements as appropriate. Accurate boundary conditions, such as inflation pressure, road contact, and mechanical loads, are essential, and models must be validated against experimental data, including footprint area, vertical stiffness, and dynamic response, to ensure reliability. Applications of these models are extensive, ranging from performance prediction (rolling resistance, cornering stiffness, and braking efficiency) to durability analysis; noise, vibration, and harshness studies [126]; and soft-soil mobility assessments, often integrating with advanced methods such as the Discrete Element Method for off-road conditions. Recent advancements include the development of high-fidelity nonlinear FE models capable of simulating complex dynamic tire behavior, simplified models [127] that maintain essential characteristics while improving computational efficiency, and the integration of FE tire models into virtual prototyping workflows, facilitating early-stage design evaluation and optimization.

A study [29] proposed to estimate tire road friction coefficients using different methods that have been widely utilized to estimate tire road friction coefficients. This narrative review provides a comparative analysis of tire–road friction coefficient estimation and describes the strengths and weaknesses of techniques. Through a road friction coefficient estimation method, using a two-wheel vehicle braking model and sliding mode control, it found a solution for active safety systems by accurately predicting friction under different conditions to control wheel slip ratios to match ideal values [128]. In [129], the authors analyze how variation in the coefficient of friction, due to the intensity of road traffic, which wears roads, affects the risk of skidding on road curvatures, thus providing information on road maintenance depending on traffic volume. High-performance vehicles require tires with optimized friction characteristics for superior handling and acceleration. Competition tires, for example, are designed to maximize grip and hysteresis for the best possible adherence. A method for estimating the road friction coefficient is presented in [130] for predicting a vehicle path in the context of the development of active lane departure warning systems. Using the Highway Safety Research Institute (HSRI) tire model, in reference [131], two methods were designed to estimate road surface friction coefficients: one indirectly via the utilization friction coefficient, the other by transforming the HSRI equation into an explicit form. A simplified model for calculating the friction coefficient of tires, identifying the factors which significantly influence friction, is proposed in [132]. Fuel efficiency can be improved by approximately 1% for every 5–6% reduction in rolling resistance, according to [133].

Theoretical and numerical models (Magic Formula, Dugoff, brush, LuGre, FEA, etc.) are essential for simulating and predicting tire behavior. They are applicable in vehicle dynamics simulations, tread pattern optimization, and the estimation of longitudinal and lateral forces. However, these models have limitations (e.g., high computational cost for FEA and simplifications in semi-empirical models). Future directions could include integrating artificial intelligence and machine learning to process large sensor data sets and improve the accuracy of TRFC estimation under varied and real-time conditions.

To facilitate effective model selection, it is important to recognize the inherent trade-off between computational cost and physical fidelity across different tire modeling approaches. Empirical models (e.g., Magic Formula) are most appropriate for real-time control and vehicle simulation applications, where computational efficiency and parameter fitting from test data are prioritized. Semi-empirical or analytical models (e.g., brush and LuGre) offer a balance between physical interpretability and moderate computational demand, making them suitable for conceptual design or control algorithm development. Finite element-based models provide the highest degree of structural and material detail, enabling comprehensive analysis of stress distribution, fatigue, and wear, though they are computationally intensive. Finally, high-fidelity dynamic models such as FTire offer an optimal choice for scenarios requiring accurate prediction of tire behavior over complex road inputs and high-speed dynamic responses, where simulation precision is more critical than computational speed.

4. Discussion

The tire–road friction coefficient is not a static value, but rather the result of a dynamic and complex interaction between numerous factors. Friction mechanisms—adhesion, dominant on dry, smooth surfaces, and hysteresis, on rough or wet surfaces—are complementary and influenced by a wide range of variables. An analysis of tire–road interaction can be structured around the concept that the coefficient of friction is not determined by a single factor but rather results from a complex interdependence of multiple variables. The way each of these factors interacts with others and how optimizing one may have beneficial or adverse effects on the rest is summarized in the following paragraphs:

- Tire Compound: Soft rubber compounds offer better grip, thus yielding a higher coefficient of friction, but they tend to wear out more quickly and are sensitive to temperature changes. In combination with temperature, the tire compound must be selected to remain sufficiently adhesive at real operating temperatures without becoming too soft or too rigid. Although softer compounds provide increased grip, they may require higher inflation pressures to compensate for excessive deformation.
- For rubber, there is a close relation between sliding friction (especially at low speeds) and viscoelastic properties. Softer rubber (or rubber at a higher temperature, and thus more compliant) shows increased friction under relevant regimes [134].
- Enhanced formulations incorporating nanomaterials can reduce rolling resistance (RR) by 5–7% while maintaining durability.
- Tread Pattern: The tread design influences how effectively water or debris is evacuated and the extent of direct contact with the road surface. Treads with numerous grooves and protrusions perform well on wet or muddy roads but may reduce actual contact on dry asphalt, especially if combined with improper inflation pressure. In terms of surface interaction, an off-road tread on smooth asphalt may significantly reduce grip compared to a slick tire designed for that specific surface. Wet-condition treads (e.g., multiple grooves and channels) increase grip on slippery surfaces but also raise rolling resistance due to increased volume and deformation.
- Road Surface: The texture and material composition of asphalt mixtures significantly affect tire grip. Smooth roads provide limited roughness, making tire composition and temperature more critical. On rough-textured or wet surfaces, tread design and inflation pressure are key to maintaining effective contact. Macroscopic roughness influences hysteresis through localized deformation. Road moisture changes the

adhesion mechanism—from direct bonding on dry roads to hysteresis-dominated interaction in wet conditions.

None of the studies reviewed fully address all the mechanisms, such as micro-adhesion reduction, altered hysteresis, lubrication by fine particles, and effects on cornering stability, in the context of road dust between tire treads and pavements. Road dust plays a significant role in modifying tire–road interaction mechanisms, thereby influencing overall vehicle dynamics and safety performance. Some research which can be mentioned is [135–137]. At the micro-scale, dust particles form a thin intermediate layer between the tire tread and the pavement surface, which reduces the real contact area between the rubber and aggregate and consequently diminishes the adhesive component of friction. In addition, the presence of dust alters the viscoelastic deformation of the tire tread by smoothing the effective surface roughness perceived by the rubber. This change weakens the hysteretic contribution to friction, particularly at lower speeds, where energy dissipation through micro-deformation is critical. Fine dust particles, such as silica, clay, or carbonaceous matter, may also act as dry lubricants, further reducing the coefficient of friction under otherwise dry conditions. As a result, braking efficiency is typically degraded, leading to increased stopping distances, especially on smooth or polished pavement surfaces. Similarly, lateral grip during cornering can be compromised because the dust layer reduces the shear strength of the tire–road interface, causing larger slip angles and potential instability. Moreover, the nonuniform distribution and transient nature of road dust may induce variability in frictional response, leading to micro-slippage and fluctuations in braking torque, commonly referred to as "μ-split" conditions. These effects collectively highlight the importance of considering road dust as a key factor in understanding and modeling tire–road interaction behavior.

- Temperature: Temperature directly affects the elasticity of rubber: too cold and a compound becomes rigid; too hot and it becomes excessively soft. Increased temperature softens the rubber (reducing its viscoelasticity), which in turn lowers internal hysteresis and therefore the coefficient of friction. Proper inflation can help the tire reach and maintain its optimal operating temperature more efficiently. Temperature is interdependent with wheel load: excessive load increases heat buildup and accelerates wear. Theory predicts that under isothermal conditions the coefficient of friction decreases with load, which is more pronounced for the adhesion than for the hysteresis contribution. This result is found to be in fair agreement with the measured friction curves confirming the contact mechanical approach of the theory [138]. Temperature significantly influences tire–road interaction through complex thermo-viscoelastic mechanisms. As temperature increases, the rubber's modulus decreases, allowing greater conformity to pavement micro-texture and enhancing adhesive friction at moderate levels. Elevated thermal conditions also promote molecular mobility, facilitating interfacial bonding and improving grip within an optimal viscoelastic range. However, excessive heating causes over-softening of the tread rubber, reducing shear stiffness and promoting slip. Frictional heating at asperity contacts, flash temperature, further amplifies local softening, diminishing the hysteretic component of friction and potentially inducing frictional instability [139]. At high temperatures, the viscoelastic hysteresis losses decline because the difference between storage and loss moduli narrows, reducing energy dissipation and overall friction efficiency. This thermal–mechanical feedback loop between heat generation, deformation, and slip can destabilize traction. Consequently, an optimum temperature window exists in which grip is maximized; outside this range, either excessive stiffness at low temperatures or over-softening at high temperatures leads to reduced traction, accelerated wear, and potential thermal degradation of the tread compound.

- Wheel Load: A higher wheel load generally increases the contact patch area, thereby enhancing grip—up to a certain point. When high load is combined with low inflation pressure, it can lead to excessive deformation and performance degradation. Load distribution must be analyzed in conjunction with vehicle type and road conditions. Increased load often requires higher pressure to control deformation and manage friction. Electric vehicle (EV) tires, subject to higher weights, may experience accelerated wear and contribute to particulate emissions. The use of biomaterials is being explored to mitigate these impacts.
- Tire Pressure: Inflation pressure is one of the most critical and easily adjustable parameters. It affects the size and shape of the contact patch, thus influencing the effectiveness of the tread and grip. The ideal pressure depends on temperature, load, and road surface; for instance, in racing, pressure is adjusted based on the expected track temperature. Tire wear increases with pressure, load, and friction, especially under high speed and load conditions. Higher pressure reduces lateral deformation and the contact area, leading to lower rolling resistance but potentially also to a reduced coefficient of friction due to smaller contact footprints.

The air pressure in tires is responsible for tire stiffness and cannot be reduced essentially. Low pressure results in strong wear of tires and weak lateral guidance of the vehicle [60,140]. An increase in pressure leads to a decrease in the adhesive friction and thus a decrease in the coefficient of friction. A lower inflation pressure, and consequently a less stiff carcass, results in more rotation of the contact patch; this leads to lower lateral force for the same slip angle, which results in lower cornering stiffness at high vertical loads [141]. An increase in slip velocity leads to an increase in adhesive friction and thus an increase in the coefficient of friction. Temperature plays a dual role: initially, as temperature increases, the rubber's rigidity decreases, enhancing its adhesion to the surface and further increasing the friction coefficient. However, at higher temperatures, the reduction in hysteresis losses begins to counteract the increase in adhesive friction. When the decrease in hysteresis loss surpasses the gain in adhesive friction, the friction coefficient begins to decrease [142]. Table 3 presents the influence of tire pressure on performance and durability.

Table 3. Influence of tire pressure on performance and durability. Sources: [60,140–142].

Low Pressure	High Pressure
Larger but uneven contact patch	Smaller contact patch, smaller friction coefficient
Increased grip at low speed	Low grip, risk of skidding
Increased wear on the edges of the belt	Increased central tread wear
Increased risk of overheating	Stiffer suspension, reduced comfort
Strong wear of the tire and weak lateral guidance	

High speeds increase heat generation and cause repetitive changes in the contact patch, thereby influencing the coefficient of friction over time.

Optimizing a single variable from those previously mentioned (e.g., increasing tire pressure) may improve the coefficient of friction on a specific surface but may degrade performance under other conditions (e.g., low temperatures or wet roads). Therefore, effective optimization must account for the interaction among all these factors, depending on the intended purpose of the vehicle, whether performance, safety, durability, or energy efficiency.

Tire composition (natural vs. synthetic rubber and inclusion of additives such as silica and carbon black), tread design, temperature (ambient, tire, and road), road surface texture, load, and inflation pressure all interact. For instance, a softer tire that offers increased grip may generate more heat, affect hysteresis, and accelerate wear. Below is Table 4, illustrating the factors influencing the tire–road friction coefficient.

An increase in pressure leads to a decrease in the adhesive friction and thus a decrease in the coefficient of friction. An increase in slip velocity leads to an increase in adhesive friction and thus an increase in the coefficient of friction. An increase in temperature leads to a decrease in the rigidity of rubber wheels, the adhesion friction increases, and the coefficient of friction shows an increasing trend. After the temperature increases to a certain extent, the growth trend of the adhesion friction slows. The hysteresis loss of a rubber wheel gradually decreases with the increase in the temperature. When the reduction in the hysteresis friction exceeds the increase in the adhesion friction, the friction coefficient shows a decreasing trend. This leads to the coefficient of friction, with the increase in temperature showing a trend of first increasing and then decreasing [143].

Different rubber ratios (RRs) have a great influence on rubber friction. When the slip velocity is low, rubber with a higher rubber ratio shows better friction characteristics. When the slip velocity is low, the higher the RR of the specimen, the higher the friction coefficient. In the case of low velocity, no water film is produced, and the specimen, whose contact area is higher, possesses the higher friction coefficient. Furthermore, when there is no water film, an increase in velocity will increase the friction coefficient. However, an increase in load makes the friction coefficient decrease sharply. Load influences the friction coefficient. It has been found that the greater the load, the smaller the friction coefficient. Under the condition of a large load, a specimen slips, the heat generated by friction is larger, and a water film forms more easily on the contact surface. Thus, the coefficient of friction is greatly reduced [144].

Results showed that the macro-texture characteristics of pavement shifted from rough to flat after wear, with peak features gradually disappearing and texture directionality transitioning from multi-directional to the traffic direction. Wear caused a decrease in material at the surface peaks and valley areas, while accumulating material in the core area. The dynamic friction coefficient (DFT40, DFT60, and DFT80) of asphalt pavements initially increased (peaking at around 3000 wear cycles) before decreasing and eventually stabilizing [145].

Theory predicts that under isothermal conditions the coefficient of friction decreases with load, which is more pronounced for the adhesion than for the hysteresis contribution. This result is found to be in fair agreement with the measured friction curves confirming the contact mechanical approach of the theory [138]. In Table 4 the main factors and their typical effects are presented.

Tire compound + temperature + pressure represents a simple rule for reducing rolling resistance (RR) under optimal conditions.

There are inherent trade-offs in optimizing tire performance. A higher coefficient of friction may come at the cost of increased rolling resistance or faster wear, impacting fuel efficiency and durability. Manufacturers must balance these aspects depending on the intended application of a tire: safety, efficiency, and durability.

How environmental conditions, particularly wet and dry surfaces, affect tire–road friction characteristics is also analyzed in [54]. Using experimental datasets and identifying friction behavior through the Magic Formula by Pacejka, researchers found that pavement type significantly influences friction variability. A brush model was also applied to simulate the dynamic interaction between tires and various road surfaces. The findings underscore the critical role of pavement conditions in determining friction behavior and highlight the safety implications for real-world driving scenarios.

The pressure dependency of the kinetic friction coefficient in rubber–road interactions is also explored in [152]. Several factors which contribute to this dependency are identified:

contact area saturation, nonlinear viscoelastic behavior, surface roughness, adhesion, and notably frictional heating. Among these, frictional heating is identified as the dominant cause, as it softens the rubber, expands the contact area, and alters the viscoelastic friction contribution. Because rubber temperature depends on its sliding history, the coefficient of friction becomes a time-dependent variable. The tribological performance of tire–road contacts depend especially on the contact temperature; this was found in [148].

Table 4. Typical effect of each factor.

Factor	Typical Effect	Notes	References
Tire compound	Softer rubber, softer viscoelastic compounds offer higher friction coefficients, especially at low slip speeds	Softer rubber conforms better to surface asperities and has higher hysteretic and adhesive contribution; compound glass transition controls temperature sensitivity.	[10,62–69,90,144,146]
Tire temperature	TRFC typically increases with moderate warming toward optimal tread temperature, then can decreases if overheated	Temperature changes rubber viscoelasticity and adhesion; there is an optimal window near which hysteretic loss and adhesion produce maximum grip.	[77–79,90,142,143,147,148]
Tread pattern	Pattern that evacuates water and provides biting edges offers higher wet friction coefficient	Tread channels control water evacuation, prevent hydroplaning; tread blocks provide mechanical interlocking on rough surfaces; depth affects contact and aquaplaning threshold.	[10,48,70,146,149,150]
Road surface/texture	Coarser texture and high micro-roughness offer higher friction coefficient (up to a point); polished and/or contaminated surfaces offer lower friction coefficient	Tread rubber compound in the lower slip region is most prominent, which is also where vehicles operate most of the time.	[42,50,52,54,55,71–74,145,151]
Tire inflation pressure	Higher pressure offers smaller contact patch and often lower grip (reduced hysteretic contribution); very low pressure may generate weak lateral guidance of a vehicle	Surface roughness determines hysteretic friction (rubber deformation) and real contact area; aggregate type (porous or dense) and contamination with ice or oil change this coefficient dramatically.	[50,60,80–84,151]
Wheel load (vertical force)	Friction coefficient often decreases with increasing normal load (contact area/pressure nonlinearity); peak friction force increases, but friction coefficient often falls	Pressure changes contact area, contact pressure distribution, and tread block stiffness; both under- and over-inflation hurt effective grip vs. optimum.	[80–82,138,142,144,147,151,152]

Tire tread wear was studied in [149] using indoor experiments and advanced analytical modeling. Controlled tests with the FE Grosch wheels model produced consistent results, showing low variability across multiple trials. A refined wear model based on local friction states significantly outperformed traditional approaches, achieving a root-mean-squared error 33% lower than those of the standard models. Incorporating tread temperature further improved accuracy by 5%. The model also identified optimal combinations of vertical load and driving speed that minimize tread wear. These insights support the development of driving strategies and tire designs that enhance durability and efficiency under various operating conditions.

The application of finite element analysis in passenger tire studies and experimental validation methods are highlighted in [90]. The paper also traces the evolution of tire–road contact algorithms and examines friction modeling techniques. It summarizes the main findings on tread rubber compound design, particularly using hyper-viscoelastic models for both the tread top and base layers. Additionally, the review addresses the impact of temperature on tire performance and identifies research gaps, emphasizing the need for more integrated and advanced modeling approaches. Also, the SAE J2452 standard includes all three parameters, pressure, load, and road surface, to enable realistic measurements [151]. Several mechanisms, such as contact area saturation, nonlinear viscoelasticity, surface roughness skewness, adhesion, and frictional heating, contribute to the pressure dependence of rubber friction coefficients [42]. Among these, frictional heating is the dominant factor, as it softens rubber, increases contact area, and reduces viscoelastic friction. Because rubber temperature depends on sliding history, the friction coefficient is time-dependent.

In [153], experimental and model-based methods for estimating tire–road friction are reviewed, highlighting widely used algorithms and their effectiveness. It summarizes strengths and limitations of current approaches, providing a comprehensive overview to guide researchers in selecting and developing accurate friction estimation techniques for tire–road interaction applications.

Sustainability considerations in tire production have increasingly shifted attention toward alternative raw materials for rubber and its compounds. A study presents a systematic sustainability evaluation of rubber, fillers, and oils, emphasizing environmentally friendly and natural-origin substitutes. Using a structured decision-making approach, the authors assessed alternatives covering approximately 90% of the materials typically used in tire production by masses. The analysis identified Russian dandelion as the most sustainable rubber source, bamboo as a promising filler to partially replace carbon black and silica, and palm oil as the most suitable softener. While Hevea remains the dominant natural rubber resource, the findings suggest that more sustainable substitutes are viable and can reduce reliance on synthetic, high-emission, and non-renewable materials [154].

Research on sustainable rubber sources has emphasized the need to diversify beyond Hevea brasiliensis to meet growing demand and reduce environmental pressure. The Russian dandelion (Taraxacum koksaghyz) has been identified, once again, as a promising alternative, as its roots can yield significant amounts of natural rubber [155]. Such alternative crops could help stabilize supply chains for tire production while ensuring that rubber quality remains consistent enough to preserve reliable tire–road friction performance.

In parallel, a range of bio-based oils have been investigated to replace petroleum-derived plasticizers in tire compounds. Epoxidized palm oil (EPO) has shown promising results as a biodegradable and cost-effective alternative. The study in [156] reports that EPO enhances filler dispersion and polymer–filler interaction, resulting in improved tensile strength, modulus, elongation, abrasion resistance, and rebound resilience and reduced heat buildup at low loadings, making it a strong candidate for tire applications. Other natural oils, such as castor, soybean, sunflower, and fried palm oil, have also demonstrated comparable or improved performance relative to conventional aromatic oils, with certain formulations offering enhanced heat resistance and ozone durability. Since plasticizers directly influence the viscoelastic behavior of tread compounds, these renewable oils are especially relevant for maintaining grip, wet traction, and abrasion behavior, thereby contributing to both sustainability and reliable tire–road friction performance [157].

Efforts have also focused on biofillers and agricultural products to replace carbon black and silica. Incorporating cereal straw, kenaf fiber, and palm oil trunk biochar (OPTB) into rubber composites has been shown to improve tensile strength, modulus, and hardness, particularly when treated or used with coupling agents. OPTB improved dielectric and thermal stability, though trade-offs in tensile strength and elongation were observed at higher loadings [158]. These results suggest that sustainable fillers can partly substitute traditional reinforcements while preserving or even tailoring the stiffness, wear resistance, and surface interaction of tire treads. As such, biofillers may contribute not only to lower environmental footprints but also to the optimization of TRFC under diverse operating conditions.

The composition and viscoelastic properties of a tire compound significantly influence the tire–road friction coefficient (TRFC), particularly under varying thermal and surface conditions, by affecting energy dissipation, adhesion, and hysteresis mechanisms at the contact interface. A synthetic table detailing the influence of these components is presented in Table 5.

Table 5. Influence of tire composition and construction on TRFC.

Components	Influence on TRFC	Advantages/Disadvantages	References
Natural rubber (NR)	Reasonable wet performance but generally outperformed by current SSBR/silica systems designed for wet grip	Faster wear at high temperatures Epoxidized Natural Rubber (ENR) improves wet grip and friction, especially under certain loads/surface roughness. The epoxidation, filler can shift the dynamic properties/hysteresis to improve grip	[10,62,63,154,159]
Synthetic rubber (SBR)	SBR exhibits better tire–road friction in wet conditions than NR and maintains stability at higher operating temperatures	Durable, easily customizable, but higher fuel consumption Synthetic rubbers like (functionalized) SSBR tend to give better wet grip	[63,64]
Silica	Increases TRFC on wet and stable surfaces in cold conditions	Low fuel consumption, good grip; "Green Tire" silica reduces consumption by ~5% The coefficient of friction of silica-filled SBR is higher than that of carbon black-filled SBR, both in dry and lubricated sliding	[63,65,66,90,160]
Carbon black	Good TRFC at high temperatures, but decreases in wet conditions	Excellent abrasion resistance; ideal for off-road	[67,68,161]
Sulfur	Stiffness increases; affects hysteresis, particularly in dynamic contact with road surfaces; higher friction coefficient	Sulfur vulcanizates are prone to oxidative aging, especially under UV or ozone exposure As sulfur content increased, the hardness and abrasion resistance increased significantly	[69,161–163]
Biomaterials and resins	TRFC increased in wet conditions; increased wear and consumption	Bio-resins often have higher softening points compared to many oils or synthetic plasticizers. This helps raise viscoelastic loss at lower temperatures, which improves wet grip Sustainable, sensitive to wear	[65,164,165]
Plasticizers	Increased grip in cold weather; hysteresis and slightly higher consumption	Plasticizers affect hysteresis losses Increased energy dissipation, which is good for wet grip Improved elasticity and comfort may increase fuel consumption	[161,166]
Accelerators/ activators	Accelerators and activators do not directly increase or decrease the friction coefficient; they modify the crosslink network, which in turn affects viscoelastic hysteresis; results influence wet grip and rolling resistance; elastic modulus/stiffness affects dry adhesion and low-speed traction	Improves structure formation and strength	[85,161,162]

The scientific contributions of this article lie primarily in the synthesis and structuring of current knowledge on the tire–road friction coefficient, offering an updated and integrated understanding of the mechanisms of friction and the multitude of factors that influence them. A central achievement is the identification of persistent research gaps. In addition, the article provides an analysis of existing theoretical and numerical models of tire–road interaction, such as the Magic Formula, LuGre, Dugoff, Burckhardt, Fiala, brush, and finite element approaches, outlining their advantages, main features, and applications. Another important contribution is the recognition that this coefficient is not a static parameter but the dynamic outcome of complex interactions between tire composition, tread design, inflation pressure, temperature, road surface, and wheel load. The study shows that optimizing one variable may have positive or adverse effects on others, which underscores the need for a holistic approach.

Building on these findings, the paper also mentions future research directions that integrate artificial intelligence and machine learning to process large-scale sensor datasets and enhance the accuracy of real-time friction coefficient estimation across diverse driving conditions.

The practical contributions of the article are equally significant. By analyzing the implications of the Euro 7 regulations, which for the first time set limits on particle emissions from tire wear, the study provides valuable guidance to manufacturers for optimizing tire composition and durability. A more precise understanding of TRFC also contributes directly to vehicle safety by improving break distance predictions and vehicle handling under adverse conditions such as wet or icy roads. The paper further advances the agenda of sustainability and energy efficiency by emphasizing the development of eco-friendly tires using bio-based materials and green manufacturing processes, the reduction of rolling resistance as a means to lower fuel consumption and greenhouse gas emissions, and the management of tire wear particle emissions, including those influenced by electric vehicles, in support of urban pollution reduction and public health protection. At the same time, the article stimulates technological innovation in the tire industry by highlighting the need for new solutions adapted to electric and autonomous vehicles and for real-time friction coefficient estimation methods. Finally, the insights into the interdependence of TRFC factors and the evaluation of tire–road interaction models provide engineers and manufacturers with practical tools for optimizing tread design, material composition, and inflation strategies, thereby improving the balance between grip, durability, and rolling resistance under a wide variety of operating conditions.

The core factors: tire formula, load, pressure, road surface, and temperature, do not operate independently. They create a dynamic system where the primary link is temperature generated by the friction process itself.

- Tire Formula (e.g., rubber type, tread, and composition): This factor establishes the intrinsic viscoelastic properties of the material. It dictates the base level of adhesion (molecular forces) and hysteresis (energy dissipation). Tires designed for lower rolling resistance, for example, typically trade off some grip due to their material composition.
- Road Surface (micro- and macro-texture): Surface texture determines the available contact points and the deformation frequency of the rubber. Micro-texture influences adhesion, while macro-texture is key to hysteresis (due to bulk deformation) and also affects water drainage, which critically reduces adhesion on wet surfaces.
- Load and Pressure: These mechanical factors define the contact patch area and the nominal contact stress. Pressure primarily controls stiffness and contact shape. Load is the vertical force. The dynamic interplay means an increase in load can increase contact but simultaneously accelerate frictional heating, leading to a complex, nonlinear effect on the final TRFC.
- Temperature: The friction mechanism itself generates heat, making temperature a dynamic output that instantly becomes a key input:

- ○ Frictional Heat Generation: When a tire slips or deforms on the road, the energy dissipated by hysteresis generates heat.
- ○ Thermo-Viscoelastic Change: This heat raises the temperature within the contact patch, causing a change in the rubber's viscoelastic properties (softening or stiffening), which in turn modifies the loss modulus and thus the hysteresis component of friction.
- ○ Feedback Loop: This change in rubber properties alters the rate of heat generation and the resulting friction coefficient, creating a constant, closed-loop feedback mechanism that determines the final friction coefficient and wear rate.

The TRFC is fundamentally the sum of three distinct mechanisms: adhesion + hysteresis + wear. The final friction is determined by which of these mechanisms dominate under the current operating state. For instance, adhesion dominates on smooth, dry surfaces, while hysteresis becomes key on rough or wet surfaces due to the deformation of the rubber around surface asperities. Conditions like wet asphalt drastically reduce the adhesion component.

The Friction Performance Triangle, shown in Figure 11, illustrates the trade-offs among grip, rolling resistance, and wear resistance in tire design. Enhancing one performance attribute typically compromises the others: increasing grip (e.g., via softer compounds) improves traction but raises rolling resistance and wear; improving wear resistance (harder compounds) extends durability but reduces grip; and minimizing rolling resistance enhances fuel efficiency but may reduce traction and accelerate uneven wear. The central region represents the engineered balance point where compound chemistry and tread design optimize all three parameters simultaneously.

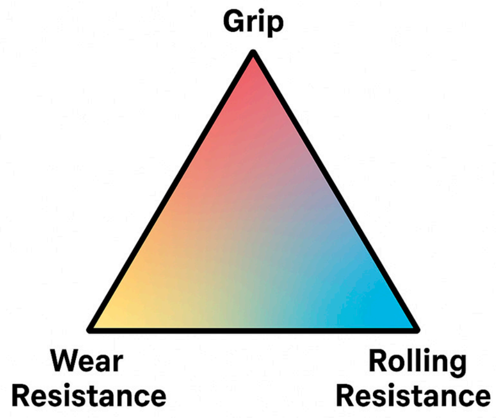


Figure 11. Friction Performance Triangle.

The wear rate is intrinsically linked to the cohesion component, which represents the energy consumed in physically tearing and degrading the rubber material. High localized strains combined with high, dynamically generated temperatures accelerate the chemical and mechanical degradation of the tire material, leading to increased wear particle generation. Therefore, the factors that increase frictional heating (high slip, high load, or an aggressive tire compound) will necessarily increase the wear rate.

4.1. Addressing RQ1: TWP Emission Reduction Strategies to Meet Euro 7 Regulations

Euro 7 introduces, for the first time, emission limits for non-exhaust particulate matter originating from tire wear (TWPs—tire wear particles), acknowledging its significant impact on air quality and public health. This regulation compels manufacturers to optimize tire composition and durability. They will be required to meet new criteria regarding compound formulation and abrasion resistance.

Tire and road wear particles (TWPs) are a growing source of non-exhaust particulate emissions, with implications for air quality, water systems, and microplastic pollution. Contemporary strategies to mitigate TWP emissions are multi-tiered, spanning material innovation, operational measures, and environmental management.

Source reduction remains the most effective approach. Advances in tire design, such as low-wear tread compounds, optimized tread geometry, and innovative fillers or additives, can substantially reduce particle generation. Complementary road surface engineering strategies, including low-abrasion asphalt mixes and texture optimization, further limit abrasive interactions between tires and pavements.

Vehicle-level and operational measures offer additional mitigation. Lower vehicle weights, torque and acceleration management, optimized brake/regenerative control, and smoother driving behavior reduce dynamic forces that exacerbate tire and road wear. These measures, together with capture and maintenance strategies, such as street sweeping, curbside filters, and stormwater treatment, help prevent TWP resuspension and downstream transport.

Regulatory frameworks and standardized testing are emerging globally, with initiatives like Euro 7 promoting microplastic reduction targets and the development of harmonized methods to quantify tire abrasion and emissions. Concurrently, monitoring and research tools, advanced particle sampling, characterization, and modelling enable evidence-based assessment of mitigation efficacy. For TWPs already mobilized, remediation and end-of-pipe solutions, including filtration systems, engineered wetlands, and advanced wastewater treatment, are being piloted, with early research exploring biodegradation or sequestration approaches.

Overall, an effective TWP control strategy (Figure 12) integrates material and pavement innovations, operational management, active capture, regulatory compliance, and targeted remediation. Multi-stakeholder projects and recent reviews provide guidance for the implementation of these complementary measures in both technical and policy contexts.

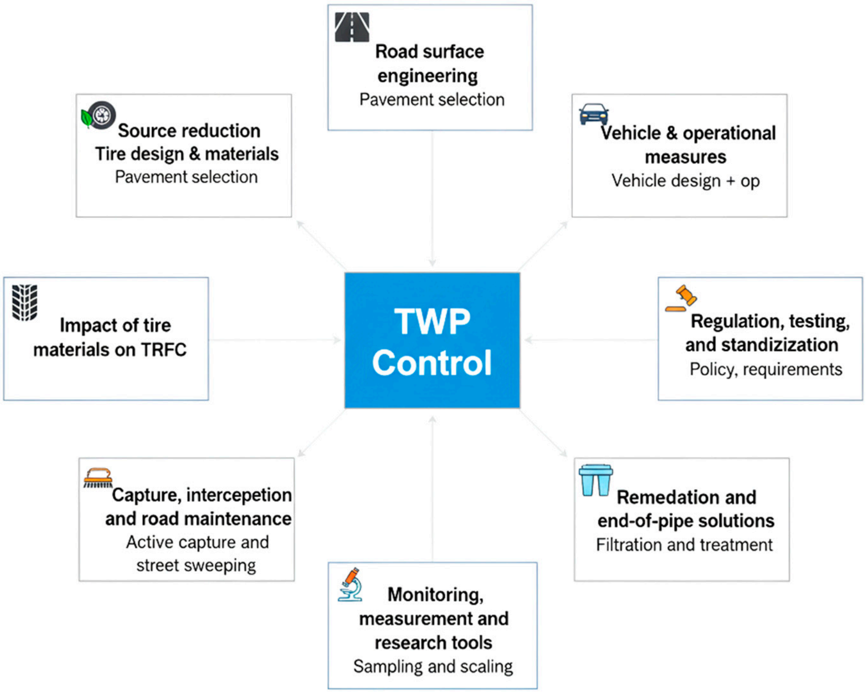


Figure 12. A strategy for TWP control diagram.

Although its focus is broader than just tire wear particles, the study [167] covers the non-exhaust emission domain (including tire wear), summarizing sources, particle compositional aspects, and mitigation. Its inclusion helps position TWP generation within the larger non-exhaust particulate problem. A wide-ranging review summarizing many literature sources on mitigation strategies for TRWPs—source reduction (tire–pavement design), capture/road cleaning, regulatory frameworks, and measurement standardization—is presented in [168]. While more about control than pure generation, it contextualizes the tribological generation mechanisms in the broader emission-control landscape. An open-access study [169], tracing tire and road wear particles from their generation, via road simulator experiments, to their environmental distribution in marine sediments, highlights the link between tire formulation, tread hardness, wear emissions, and downstream transport. This is particularly valuable for linking tribological mechanisms to environmental fate. A method to prepare a model (TWP/TRWP (tire + road material)) that mimics environmental particles in terms of morphology and composition is developed in [170]. It offers a useful methodology for tribological researchers who need reproducible particle samples for wear testing, characterization, and fate studies.

To comply with the new standards, tires must be engineered to resist wear while maintaining grip, fuel efficiency, and driving performance, a challenging balance that demands the development of new compounds, such as those incorporating nanomaterials and advanced silica.

The implementation of Euro 7 involves the adoption of standardized testing methods (e.g., real-world driving and drum testing) to measure tire wear and actual TWP emissions under urban, suburban, and highway conditions. Electric vehicles (EVs), which are generally heavier, contribute to increased tire wear. Euro 7 mandates that manufacturers develop EV-specific tires designed to minimize TWPs without compromising range or safety.

The generation of tire wear particles is governed by complex tribological processes that are strongly influenced by factors such as load, speed, temperature, and road surface texture. Among the primary mechanisms, fatigue wear [1] arises from repeated cyclic deformation of the tire tread, which induces microcrack formation and propagation, ultimately leading to the detachment of wear particles; this mechanism is particularly significant under high-load conditions. Abrasive wear [171,172] occurs through mechanical interaction between the tire tread and road surface asperities, where the hardness and roughness of the pavement critically determine the rate of material removal. Abrasive rubber wear results in more severe TWP emissions than fatigue wear does. It is easy for soft rubber to form a pattern on its surface and induce severe abrasive wear, which potentially produces more TWPs. The variables exhibit the following order of influence on the emission of 3.0 μm particles: load, slip ratio, velocity, braking time, and humidity [172]. Additionally, adhesive wear contributes to particle generation via localized welding and tearing of the rubber in regions of high contact pressure and temperature. Thermal effects further influence TWP formation, as frictional heating softens the rubber, increasing susceptibility to wear, and may also accelerate chemical degradation of the polymer matrix. Temperature has a strong influence on the particle size and even changes the wear mechanism. High temperature increases the probability of large particles [171].

Finally, tribochemical reactions at the tire–road interface can modify wear behavior by forming compounds that alter the mechanical and chemical properties of the contacting surfaces. The size of tire wear particles exhibits an approximately normal distribution in most cases, and tires with good wear resistance produce fewer particles. The quantity of particles less than 10 μm in size is much higher under water lubrication [171]. Collectively, these mechanisms underscore the multifaceted tribological nature of tire wear and highlight the importance of considering both mechanical and chemical factors in understanding TWP generation.

Some studies, such as [173], provide detailed cost–benefit assessments, estimating that a mere 10% reduction in tire wear could lead to savings of several billion euros by 2050, with tangible effects expected to begin manifesting between 2029 and 2032.

A comprehensive review of tire wear particle (TWP) emissions and measurement methodologies relevant to the development of the Euro 7 standards is presented in [174]. Reference [175] introduces a rigorous methodology applied under real-world conditions, where particles are identified using pyrolysis–GC-MS. This study provides data on the influence of driving behavior (particularly acceleration), vehicle load, and road type. The reported output amounts to up to 480 tons of tire and road wear particles (TRWPs) annually in EU27, indicating a widespread presence in the atmospheric compartment with significant implications for human health.

Another study [176] explores tire wear particle (TWP) emissions under real-world driving conditions, offering detailed emission factors. Particles were collected from urban, suburban, and roadway environments and subjected to thorough physical and chemical analysis. The study confirms the established toxicity of these emissions and provides a comprehensive assessment of their emission factors. Pollutants with the highest emission rates showed elevated values, often exceeding the Euro standards for vehicle emissions, though remaining below those from vehicles without particulate filters. Additionally, the chemical pollutants demonstrated consistent behavior across tests. Emission factors for both PM_{10} and $PM_{2.5}$ highlight the importance of tire wear as a critical contributor to airborne particulate pollution.

The influence of seasonal changes and pavement type on tire wear particle (TWP) emissions is analyzed in [177], focusing on PM_{10} and leachable toxins. Tire wear was quantified using benzothiazoles as chemical markers, with measured emission factors ranging from 0.005 to 0.22 mg/km/vehicle—values consistent with previous studies but lower than those predicted by models. No significant differences were found between pavement types, but emissions were notably lower in winter compared to summer. The results suggest that temperature plays a key role in TWP generation.

The study [178] highlights the substantial role of tire load and contact severity in wear and emissions. The authors investigated the generation of tire and road wear particles under controlled laboratory conditions using a pin-on-disc tribometer. The experimental setup enabled the measurement of both airborne and non-airborne emissions while simulating typical urban load and sliding speeds using commercial tire and road materials. The results showed that, under moderate testing conditions, particle emissions were minimal, and friction coefficients remained within acceptable limits. However, under harsher contact conditions, significant increases in friction, airborne particle concentrations, and overall emission factors were observed, indicating substantial material loss from both tire and road surfaces.

Tire development today is driven not only by performance but also by environmental regulations, particularly Euro 7. Companies such as Michelin and Bridgestone are actively investing in sustainable materials (bio-based rubbers, recycled contents, and eco-sourced silica) and eco-friendly manufacturing processes [86–88]. This marks a paradigm shift toward a holistic approach that considers the full lifecycle impact of tires.

The Euro 7 regulations will introduce specific limits on particulate emissions from tire wear (tire wear particles—TWPs):

- Restrictions on tire wear—to be assessed through standardized measurement methods (e.g., drum testing and real-world driving conditions).
- Optimization of tire composition and design—aimed at minimizing particle emissions without compromising safety or energy efficiency.

- Rigorous testing—involving validated methodologies in both real-traffic and laboratory environments.

Several recent studies provide complementary insights into the influence of driving conditions on tire wear particle (TWP) emissions.

Particle number (PN) concentrations are significantly higher during the US06 test cycle compared to the WLTC cycle, as is mentioned in [179], largely due to the more frequent and intense accelerations and decelerations in the former. The results further indicate that high PN concentrations occur at elevated driving speeds with rapid accelerations, while much lower PN levels are observed at low speeds with a similar acceleration intensity. Additionally, tire tread temperature was shown to play an important role: once a steady-state temperature threshold is exceeded, PN concentrations stabilize, although cold start conditions at low initial tire temperatures produce disproportionately high PN emissions.

In a field-oriented evaluation, [180] reported the highest TWP emissions on highways (2.8 ± 0.8 mg/g of collected particles), followed by suburban, urban, beltway, and rural routes. The analysis concluded that distance travelled and driving time are not major determinants of TWP levels. Instead, speed variations, vertical and lateral tire constraints, and traffic fluidity are identified as the most significant determinants of particle emissions.

Similarly, [181] provided comparative data on tread abrasion across different driving environments. The findings revealed that abrasion rates are between 1.9 and 5.4 times higher in urban settings relative to motorway driving, underscoring the strong influence of start–stop traffic conditions on tire wear intensity.

A complementary perspective is offered by [182]. This study showed that low-speed roads (<25 km/h), typically associated with congested traffic, accumulate greater amounts of TWPs in road dust than higher-speed roads (>40 km/h). The findings suggest that frequent stop–go conditions amplify wear and pollutant buildup, while road slope and roughness further modulate the distribution of particles.

The role of driver input was examined by the authors of [183]. This study emphasized that aggressive driving behaviors—particularly acceleration and braking—are major contributors to tire wear, with effects comparable to or exceeding those of average driving speed, thus reinforcing the significance of transient dynamics over steady-state conditions.

From an atmospheric deposition perspective, the authors of [184] measured TWP levels across sites with contrasting traffic conditions: highways (approx. 105 km/h) and mid-speed (approx. 65 km/h) and low-speed (approx. 25 km/h) roads. Their results revealed a positive correlation between driving speed and airborne TWP deposition, although traffic composition and acceleration events also played a considerable role.

Finally, a broader assessment is presented in [185]. This work quantified emission factors across urban, suburban, and highway contexts, reporting not only particle size distributions but also the degree of embedding into road surfaces. Notably, urban driving is associated with higher direct TWP emissions and reduced embedding, a result again pointing to the strong influence of stop–start driving patterns.

Taken together, these studies demonstrate that both high-speed highway driving and frequent start–stop conditions in congested traffic can significantly enhance TWP emissions, though through different mechanisms. While high speeds coupled with rapid accelerations elevate PN concentrations and airborne deposition, urban stop-and-go dynamics intensify tread abrasion and pollutant accumulation in road dust. The relative importance of each factor thus appears to be context-dependent, with speed variations and transient driving behaviors emerging as common determinants across multiple investigations.

This integrated approach is expected to reduce urban pollution and stimulate innovation within the tire manufacturing sector.

For electric and autonomous vehicles, the most significant differences compared with conventional vehicles are their generally higher overall weight and greater slip ratios during operation. The increased weight results from the mass of battery systems and additional sensors or control hardware, which in turn elevate the normal load on the tires and influence contact stress, heat generation, and wear behavior. Meanwhile, electric powertrains deliver instant and high torque at low speeds, often leading to larger slip ratios during acceleration or regenerative braking. Similarly, autonomous control algorithms may induce frequent micro-adjustments in traction or braking, further contributing to slip variability. These factors collectively alter the tire–road interaction dynamics, affecting friction characteristics, rolling resistance, and tread durability compared to conventional internal combustion vehicles.

The rapid deployment of electric vehicles (EVs) and the emergence of autonomous driving technologies are reshaping the traditional understanding of tire–road interaction. While EVs contribute to reducing tailpipe emissions, their specific characteristics, such as higher curb weight, instant torque delivery, and regenerative braking, pose new challenges for tire wear and friction dynamics. Some studies have highlighted that these factors can accelerate tread abrasion and increase the generation of TWPs, thereby raising concerns over non-exhaust emissions and long-term road surface degradation.

At the same time, autonomous vehicles (AVs) introduce distinct operational patterns that affect TRFC estimation and control. Automated driving relies heavily on precise friction information to ensure stability, safety, and efficiency under variable road conditions. However, the altered torque profiles, steering strategies, and eco-driving algorithms adopted in AV systems may change the way tires interact with pavement, influencing both wear rates and friction demands.

Together, these technological shifts create a dual challenge: the environmental impact of increased TWP emissions from EVs and the engineering challenge of developing robust friction coefficient estimation and control methods suitable for AVs. Addressing these issues is mandatory for advancing sustainable mobility, as it requires both a deeper understanding of tire–road interaction under new vehicle dynamics and the development of innovative mitigation strategies.

An overview of the current state of knowledge on tire wear particles that explicitly emphasizes the impact of vehicle electrification is presented in [186]. The authors conclude that the higher curb weight and instantaneous torque delivery characteristic of electric vehicles (EVs) can exacerbate tire wear, thereby increasing non-exhaust particulate matter emissions and altering frictional dynamics at the tire–road interface. This review establishes a broad framework for understanding why EVs represent a growing concern in friction coefficient and TWP management.

In the context of autonomous driving, [187] (PMC) investigates tire wear in automated articulated platforms. The study demonstrates how mass distribution, driving torque, and control strategies in automated vehicles can significantly influence tire wear. Moreover, it proposes active suspension and control measures as potential mitigation strategies, directly linking vehicle automation to tire wear management and frictional stability.

Similarly, ref. [188] reviews the role of tire wear in microplastic pollution and discusses how the specific attributes of battery electric vehicles (BEVs), notably their higher mass and torque, contribute to increased tire wear rates. The findings further underscore that tire abrasion contributes to 5–30% of road transport particulate matter emissions.

A comparative perspective is offered by [189]. This study quantifies emissions from both internal combustion engine vehicles (ICEVs) and EVs, demonstrating that while EVs effectively reduce exhaust pollutants, they can contribute more significantly to non-exhaust sources, particularly tire wear. The analysis highlights operational factors such as regenerative braking strategies and vehicle mass, both of which alter the dynamics of tire–road interaction.

On the methodological side, efforts to address friction estimation in autonomous vehicles are reflected in two studies. The first, ref. [190] develops a machine learning framework for accurate, real-time estimation of TRFC under varying conditions. This work emphasizes the importance of robust estimation algorithms for ensuring safe autonomous driving in the presence of altered dynamics. The second [191] proposes novel estimation techniques and discusses their sensitivity to vehicle load and drive torque. Given that EVs and AVs inherently modify these parameters, the study demonstrates the growing need for advanced estimation strategies tailored to new vehicle architectures.

All these contributions demonstrate that electrification and automation introduce significant challenges for tire–road interaction research. EVs increase tire wear due to higher mass and torque, while AVs demand more sophisticated friction estimation to ensure safe operation under complex control strategies. Addressing these issues requires integrating environmental concerns, such as microplastic emissions, with engineering solutions, such as active control and advanced estimation algorithms.

Potential solutions revolve around compound innovation and tread geometry optimization. Advances in bio-based and functionalized elastomers combined with high-dispersion silica and novel coupling agents can reduce hysteresis losses and enhance abrasion resistance without significantly sacrificing traction. Replacing petroleum-derived plasticizers with bio-oils further reduces environmental impact while stabilizing viscoelastic properties. On the structural side, optimizing tread stiffness, groove depth, and sipe orientation helps distribute contact stress more uniformly, thereby minimizing localized wear and particle detachment. Numerical tools such as finite element modeling and frictional wear simulations are increasingly used to balance competing objectives, low rolling resistance, adequate grip, and minimal TWP generation across climatic and road conditions.

Overall, the findings suggest that a system-level design approach integrating sustainable materials with data-driven design optimization offers the most promising route to meet the Euro 7 TWP limits while maintaining performance and safety. However, harmonized testing protocols and standardized TWP measurement methods remain essential for comparing results across studies and validating these emerging solutions.

4.2. Addressing RQ2: Technical Pathways and Challenges for Real-Time TRFC Estimation

Unlike easily measurable variables, such as wheel speed or yaw rate, friction cannot be directly sensed in real time. Instead, it must be estimated using physical models, observers, or data-driven approaches.

One of the most established approaches is the slip-based [192] or effect-based method. Here, the estimator relies on the relationship between wheel slip (longitudinal or lateral) and the generated tire force. By combining wheel dynamics with measurements of torque, wheel acceleration, and vertical load, it is possible to compute an instantaneous estimate of the friction coefficient as the ratio of tire force to normal load. For instance, during braking, wheel deceleration combined with known brake torque reveals the longitudinal force, which, when normalized by load, gives a friction estimate. A running maximum of this value can serve as the current road friction level. Such methods are attractive because they require only standard sensors (wheel speed, torque, and an estimate of load transfer), making them computationally light and suitable for real-time embedded systems.

Many studies use state observers [193], such as extended Kalman filters (EKFs), unscented Kalman filters (UKFs), or even particle filters. These observers treat the friction coefficient as a slowly varying state to be identified alongside vehicle states like lateral velocity and yaw rate. The bicycle model, in combination with tire models such as Fiala or

Dugoff, provides the framework for predicting forces. By fusing steering angle, yaw rate, lateral acceleration, and wheel speeds, the observer can infer the friction coefficient even during normal driving.

Another practical approach is event-based estimation. During ABS [194], traction control, or stability control interventions, the system naturally explores the limits of adhesion. By observing the peak forces just before intervention or at the onset of wheel slip, the estimator can quickly identify the maximum available friction. Event-based methods are highly accurate at the cost of infrequency: they only provide information during active maneuvers, not during steady driving.

In the future, the development of real-time TRFC estimation methods will be essential. Although some progress has been made, for example, using sensor-based models, the modeling of combined environmental factors (e.g., water, ice, and dust) remains a complex challenge. Electric and autonomous vehicles are redefining tire requirements. EVs, with their higher weight and torque, require specially designed tires to manage the increased load, transmit higher forces, and reduce noise, differentiating them from traditional tires.

When some sensors on a vehicle fail, it can exchange information with other vehicles to obtain data about friction coefficients. In addition, the vehicle can also modify the estimated value of the TRFC by exchanging data with a camera on a signal light [29].

As autonomous and electric vehicles become increasingly prevalent, the development of advanced and predictive models [195–197] is essential. Other models integrate sensor data [198–200], such as pressure, temperature, speed, humidity, tire compound parameters, and road surface characteristics. A promising future direction lies in the application of deep neural networks [201] or machine learning techniques to estimate, in real time, both static and dynamic friction coefficients across a wide range of driving scenarios (wet roads, snow, and degraded surfaces). Such systems could enable the active adaptation of brake and stability control mechanisms, thereby reducing tire wear, enhancing safety, and improving energy efficiency.

With the advent of advanced sensors and machine learning, data-driven methods [29] are gaining momentum. Cameras and LiDAR can classify road conditions (dry asphalt, wet pavement, ice, or snow) before the tires even make contact. This anticipatory capability is valuable for predictive control, enabling vehicles to adapt early. When combined with classical slip-based or observer-based estimates, vision systems provide a prior that accelerates convergence and improves robustness. The main challenges are generalization across varying lighting and weather conditions, as well as the need for large, labeled datasets.

Recent studies summarized in this work demonstrate that combining physics-based observers with machine learning correction layers produces real-time estimators that are both interpretable and adaptive. New AI-enhanced estimators could achieve higher accuracy during transient maneuvers, early detection of low-friction surfaces, and improved generalization across varying road conditions. Moreover, by integrating exteroceptive data from cameras or LiDAR, these models can anticipate changes in friction before tire contact, which is particularly valuable for electric and autonomous vehicles operating with smoother torque profiles and higher vehicle masses. However, challenges remain in ensuring model transparency, managing computational load on embedded controllers, and achieving robust performance under sensor failures. Overall, the literature indicates that AI-based TRFC estimation substantially improves robustness and adaptability compared with classical model-based methods, particularly when implemented as hybrid systems that combine data-driven learning with physical modeling constraints.

The analysis highlights the need for accurate estimation and optimization of friction coefficients, which is key for vehicle safety and performance, especially in varying climatic and operational conditions. The dependence of friction coefficients on the instantaneous, coupled state of all these factors is why the literature indicates that AI-enhanced estimators, particularly hybrid systems, are necessary. These systems can process the complex, transient interactions of the core factors more effectively than classical models, which struggle to account for all combinations of external agents (water, ice, and dust) and varying operational conditions.

The modeling landscape for tire–road interaction is diverse, encompassing empirical, analytical/physical, and data-driven methods. While these models are essential for vehicle dynamics simulation and safety systems (e.g., ABS and ESP), they suffer from fundamental limitations regarding parameterization, generalization, and transparency. Most conventional models, particularly the widely used semi-empirical models, are inherently limited by their reliance on extensive, carefully calibrated experimental data, which compromises their ability to generalize about new operating conditions:

- Reliance on fitted parameters: Models like the Magic Formula achieve high accuracy in fitting real data. However, this accuracy is attained through a large number of empirical fitting parameters (e.g., stiffness factor, peak factor, and curvature factor) These coefficients must be determined experimentally for every specific tire–road combination, making the model a function of the experimental data rather than a universal predictor.
- Degradation and lack of generalization: Traditional analytical models depend heavily on accurate physical parameters and well-defined slip conditions. Their performance degrades significantly when environmental factors, like surface wetness, temperature variation, or uneven road textures, introduce uncertainties at the tire–road interface. Consequently, they struggle to generalize outside of the specific, well-controlled conditions under which their parameters are derived.
- Computational cost for high fidelity: Highly detailed physical models, such as the FTire model or high-fidelity FEA models, offer comprehensive realism, including thermal effects and dynamic wear modeling. However, this fidelity comes at the cost of being extremely resource-intensive and having a high computational cost, which limits their utility for real-time control applications in vehicles.

The emergence of data-driven approaches, including those using fuzzy logic and artificial intelligence (AI) (e.g., neural networks), holds significant promise for advancing TRFC estimation but introduces a new set of critical challenges:

- AI-driven estimators can advance beyond conventional model-based observers by learning complex, nonlinear relationships between tire, vehicle, and environmental variables directly from noisy sensor data. This capability allows them to adaptively infer friction levels, making them superior to traditional methods that struggle with uncertainties introduced by combined environmental effects.
- The ability of AI models to learn these “complex, nonlinear relationships” leads to the “black box” problem, where the decision-making process is opaque and lacks transparency. A variant could be moving towards hybrid systems, combining data-driven learning with physical modeling constraints, producing estimators that are both adaptive and interpretable. This necessity for interpretability points directly to the lack of transparency in purely data-driven models.

AI models are inherently data-dependent. Achieving high performance requires massive, high-quality, labeled datasets that cover all possible operating conditions. This dependency creates two main risks:

- AI models, especially those using external sensors like cameras for TRFC estimation, face significant challenges in generalization across varying lighting and weather conditions.

- The need for large, labeled datasets is a continuous challenge in development. Furthermore, their robustness is highly susceptible to sensor failures, highlighting their reliance on continuous, clean data streams.

As a conclusion, while AI models offer the necessary adaptability for modern vehicles, the engineering challenge lies in developing hybrid models that retain the physical constraints and interpretability of traditional methods while leveraging the adaptability and nonlinear learning capabilities of AI.

The current knowledge system, while advanced in empirical modeling (e.g., Magic Formula) and high-fidelity physics-based models (e.g., FTire), exhibits significant gaps in fully coupled, predictive, and real-time modeling. The most significant lacunae are the following:

1. Fully coupled multi-physics wear models (thermal–mechanical–chemical): Advanced models like FTire account for thermo-mechanical effects and predict wear based on load, pressure, and road conditions. However, these models are often computationally expensive. There is a lack of computationally efficient and generalized models that fully integrate the thermal state, mechanical deformation, and chemical aspects (e.g., oxidative degradation and filler dispersion effects on wear) over a tire's lifespan and across a wide range of operating conditions.
2. Standardized, predictive models for tire wear particle generation and diffusion: The new Euro 7 regulations impose limits on non-exhaust particle emissions, highlighting the critical nature of this gap. Strategies to mitigate TWP emissions are multi-tiered (material innovation, operational measures, and environmental management). There is a particular need for harmonized methods to quantify tire abrasion and emissions. Specifically, the lack of a standardized prediction model that accurately forecasts the rate (generation) and fate (diffusion and environmental transport) of TWPs, linking them directly to complex, real-time tribological interactions, is a persistent gap.
3. Real-time, adaptive TRFC estimation under combined environmental effects: Real-time friction estimation is essential for vehicle safety systems. Progress has been made using hybrid AI-enhanced estimators and sensor-based models. Despite advancements, the modeling of combined environmental factors (e.g., water, ice, dust, and temperature variations) remains insufficiently developed, preventing robust, highly accurate real-time friction prediction under all complex and transient conditions. This is particularly challenging for new systems like electric and autonomous vehicles which have distinct loading and torque patterns.

5. Conclusions

This narrative review positions itself within the broader developmental trajectory of tire–road interaction research by moving beyond descriptive summaries to emphasize integrative analysis. By linking bibliometric trends, experimental findings, and technological innovations, it situates the study of TRFC not as an isolated technical parameter but as a pivotal element in the evolution toward intelligent, sustainable, and regulation-compliant mobility systems.

The study highlights that tire–road interaction cannot be described by a single parameter but results from a complex interplay of factors: tire composition and structure, road surface texture and condition, temperature, load, and inflation pressure. Optimizing one factor may positively or negatively influence others, such that an integrated approach is required.

Bibliometric and thematic analysis emphasizes the need for robust real-time friction coefficient estimation methods, which are particularly relevant for electric vehicles, where loads and torque demands are higher.

The integration of artificial intelligence and advanced numerical models is essential to support safety, energy efficiency, and reduced environmental impact. The automotive industry must therefore harmonize performance objectives with sustainability and regulatory requirements to advance toward safer and greener mobility.

Sustainability and the impact of environmental regulations, particularly Euro 7, are major driving forces of innovation in the tire industry, with a strong focus on reducing particle emissions resulting from tire wear. The transition toward Euro 7 compliance underscores the urgency of reducing tire wear particle emissions through material innovation and optimized tread geometries. Bio-based compounds, functionalized fillers, and advanced coupling technologies offer viable pathways to balance performance, durability, and environmental impact.

The forthcoming Euro 7 regulations represent a shift from traditional "back-end" environmental control, focused on mitigating emissions after their release, to a "front-end innovation" approach that drives sustainable design at the source. By setting explicit limits on tire and brake wear particle emissions, Euro 7 compels manufacturers to integrate environmental performance into tire materials, tread design, and digital modeling from the earliest stages of development. This encourages advances in low-wear compounds, bio-based rubbers, nanocomposite fillers, and AI-driven friction estimation, aligning industrial R&D with climate and circular economy goals. The regulations thu reframe compliance as a catalyst for creativity, fostering collaboration between tire producers, vehicle manufacturers, and infrastructure planners. Rather than restricting industry, Euro 7 promotes a proactive innovation ecosystem, one that designs out pollution before it occurs, enhancing both environmental sustainability and technological competitiveness in the European mobility sector.

The relationship between the tire–road friction coefficient and rolling resistance is both strong and complex, influenced by the same fundamental factors that govern the tire–road interaction. A vehicle's energy efficiency, and consequently its fuel economy, is directly and significantly affected by the rolling resistance of the tires and by optimization of the tire–road interaction.

Collectively, these findings emphasize that the future of tire technology will depend on a holistic, data-driven approach that unites vehicle dynamics, material science, and sustainability objectives to meet the evolving demands of electric and autonomous mobility.

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