Engineering Advances, 2026, 6(2), 81-95
https://www.hillpublisher.com/journals/ea/
ISSN Online: 2768-7961

A Review of the Influence of Tire Design and Construction on the Dynamic Performance of Road Vehicles

Claudiu Miclea[*], **Nicolae Burnete, Irina Duma**

Department of Automotive Engineering and Transport, Faculty of Automotive Engineering, Mechatronics and Mechanics, Technical University of Cluj-Napoca, Județul Cluj 400641, Romania.

How to cite this paper: Claudiu Miclea, Nicolae Burnete, Irina Duma. (2026) A Review of the Influence of Tire Design and Construction on the Dynamic Performance of Road Vehicles. *Engineering Advances*, 6(2), 81-95.
DOI: 10.26855/ea.2026.06.005

Received: March 13, 2026
Accepted: April 24, 2026
Published: May 28, 2026

[*]**Corresponding author:** Claudiu Miclea, Department of Automotive Engineering and Transport, Faculty of Automotive Engineering, Mechatronics and Mechanics, Technical University of Cluj-Napoca, Județul Cluj 400641, Romania.

Abstract

The present paper provides an overview of how tire type and construction influence an automobile's dynamic performance by conducting a thorough literature review. This article discusses the three primary tire types, namely summer, winter, and all-season, as well as their production methods and some of their most important mechanical and physical attributes, including tread pattern and material composition. The primary emphasis is on how these factors influence an automobile's performance in terms of braking, traction, directional stability, ride comfort, and fuel efficiency. The paper incorporates results from recent experimental and numerical research to illustrate the latest advancements in tire design and the importance of adapting tires to different operating conditions. The results highlight the need to choose tires in line with specific operating conditions in order to improve vehicle dynamic behavior and overall road safety.

Keywords

Tire construction; tire design; rolling resistance; braking distance; tire-road interaction

1. Introduction

As the only components in direct contact with the road surface, tires play a fundamental role in vehicle dynamic behaviour, including acceleration, braking, cornering, and recovery from skidding. Previous research has shown that tire condition strongly influences road safety, particularly in terms of braking distance. Efficient braking is affected by tire degradation, driver conduct, road surface conditions, and meteorological factors. The study emphasizes the significance of routine tire inspections, appropriate seasonal usage, and compliance with manufacturer specifications. Moreover, it tackles the critical hazards linked to driver distraction and the utilization of noncompliant tires, both of which substantially increase the likelihood of road accidents. The article highlights the importance of selecting tires based not only on manufacturer specifications, but also on operating conditions, seasonal requirements, and tire performance characteristics, to enhance road safety and reduce accident risk. Tire development must simultaneously satisfy the requirements for performance, durability, and sustainability. The dynamic performance characteristics such as traction, grip, braking distance, and rolling resistance are influenced by factors like material composition, layered structure, inflation pressure, and tread design [1, 2].

The variability of weather and seasons requires careful consideration while selecting tires. Utilizing inappropriate tires, such as all-season tires in extremely cold conditions, can significantly diminish traction and increase the likelihood of an accident. Recent studies highlight the imperative for uniform labeling and selection systems tailored to regional driving and climatic conditions [3-5].

Figure 1 illustrates the global distribution of annual waste tire generation, with China accounting for the largest share. As previously noted, the growing number of discarded tires reflects the high global need for tire products and further emphasizes the importance of improving tire design and construction. Material choice, structural durability, and dynamic performance characteristics have a direct impact on tire wear, service life, and, consequently, on the volume of waste generated. For this reason, progress in tire technology is important not only for vehicle safety and performance, but also for limiting early tire deterioration and promoting sustainability [6].

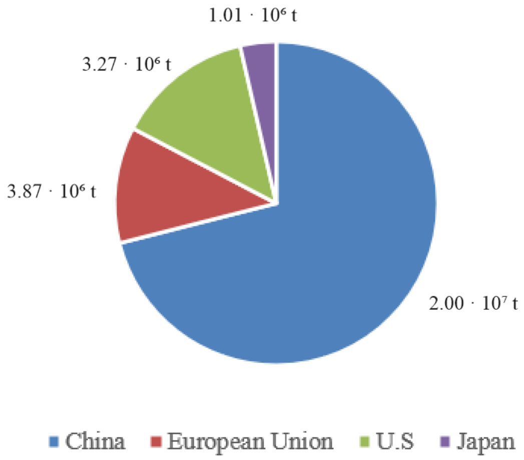


Figure 1. Annual production of waste tires [tons] [6].

Differences in consumer demands, road infrastructure, climate conditions, and regulatory frameworks have led to the segmentation of the global tire industry into four major regional markets: America, Europe, North Asia, and South Asia. Although these regions share similar manufacturing technologies and globally connected supply chains, significant variations exist in tire design, construction, and rubber compound formulations to meet specific regional requirements.

Table 1 highlights that certain performance criteria are prioritized differently across markets. The criteria are presented in descending order of priority, from the highest-ranked requirements at the top to the lowest at the bottom. However, traction and braking performance remain critical requirements in all regions [6-8].

Table 1. Overview of regional performance priorities for tire evaluation [6]

US	Europe	North Asia	South Asia
Uniformity	Traction	Traction	Load capacity
Fuel efficiency	Noise	Wear (long-distance)	Wear (long-distance)
Wear (long-distance)	Fuel efficiency	Reliability	Durability
Safety	High speed	Fuel efficiency	Economy

1.1 Objectives

This review presents a synthesis of recent studies addressing the influence of tire design and construction on the dynamic behavior of road vehicles. Particular attention is given to the role of tread pattern, material composition, internal architecture, and seasonal tire classification in driving characteristics such as braking, traction, handling stability, ride comfort, and fuel efficiency. Experimental investigations as well as numerical modeling methods are considered in order to emphasize current challenges and future perspectives in tire performance evaluation.

2. Classification and General Construction of Road Vehicle Tires

Figure 2 provides a schematic representation of the tire–road interaction, focusing on all the variables that affect a vehicle's dynamic behavior. The properties of the road's surface, operational factors like load, speed, and internal pressure, and intrinsic factors like manufacturer, size, tread pattern, structure, and wear all affect tire performance. The latter includes environmental factors like moisture, temperature, and debris, as well as physical characteristics like texture, construction materials, and pavement lifecycle. The tire slip angle α has a major impact on vehicle directional stability and plays a key role in generating lateral forces. Figure 2 summarizes the main groups of tire characteristics, operating variables, and road surface conditions that jointly determine tire–road interaction and influence vehicle dynamic behavior [9, 10].

The parameters presented in Figure 2 act simultaneously at the tire–road interface and define the mechanical response of the contact patch, influencing force generation, slip behavior, and overall vehicle dynamics.

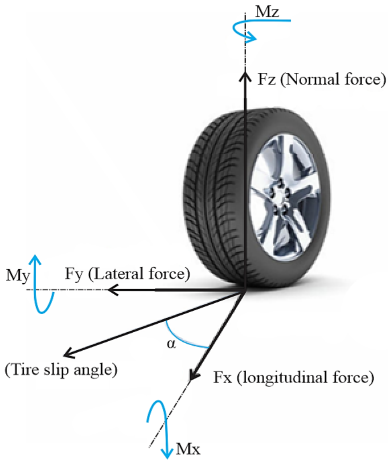


Figure 2. Factors Influencing Tire–Road Interaction [9, 10].

Table 2 presents a comparative overview of the structural and performance-related differences between radial and bias-ply tires.

Table 2. Comparison between radial and bias-ply tires [11-15]

Aspect	Radial tires	Bias-ply/Cross-ply tires
Carcass ply orientation	Plies arranged approximately perpendicular to the direction of travel (~90°), forming a flexible sidewall structure	Plies overlap diagonally, typically inclined around 35-45°, creating a stiffer carcass
Structural behavior	Higher sidewall flexibility and reduced deformation losses during rolling	More rigid structure, often associated with higher internal deformation losses
Key operational factors influencing performance	Load, inflation pressure, speed affect rolling resistance and performance	Inflation pressure affects all parameters; vertical load not significant for footprint depth
Rolling resistance	Lower	Higher
Traction (wet surfaces)	Superior	Moderate
Typical applications	Passenger cars, modern vehicles	Off-road, heavy-duty, special applications

To maintain adequate tire–road contact, the tread is designed to evacuate water from the contact patch under wet road conditions and to conform to the road surface. Consequently, each tire features unique structural and geometric design parameters. These specifications outline the tire's characteristics, which, together with the vehicle, dictate how well the vehicle performs. This implies that the tire manufacturer is subject to performance standards set by the vehicle manufacturer, which must be fulfilled. Several crucial elements are included in these requirements [11, 16-18]:

- strong tire–road interaction under all driving conditions, including longitudinal forces during braking and traction, as well as lateral forces during cornering. To ensure vehicle safety and good dynamic performance, the tire must provide stable and effective contact with the road during braking, acceleration, and cornering.

- low rolling resistance;
- reduced tire noise. The tire must minimize both external noise emissions and noise perceived inside the vehicle cabin;
- high durability and wear resistance. As the tire wears out, its properties degrade, which can lead to increased rigidity;
- shock absorption and road vibration damping capabilities;
- contribution to passenger ride comfort;
- safety and structural integrity at high-speed driving conditions.

2.1 Components of a Road Vehicle Tire

Figure 3 illustrates the individual components of the tire, offering an intricate depiction of the multifaceted structure that guarantees vehicle performance and safety from the internal base layers that provide rigidity and support to the tread, which amalgamates traction with durability [10].

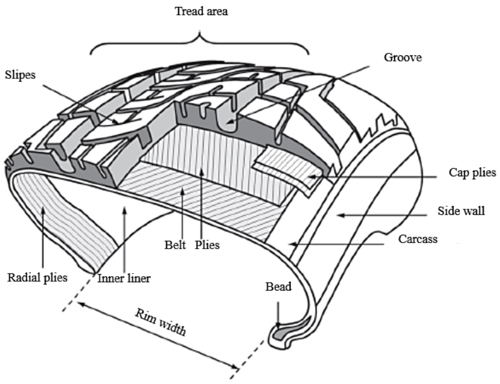


Figure 3. Schematic layout of tire structure [10].

The main structural elements of a pneumatic tire, together with their functions and typical materials, are summarized in Table 3.

Table 3. Structural components of a pneumatic tire and their primary functions [1, 3, 5, 10, 16, 17]

Tire component	Main function	Typical materials / key remarks
Tread	Protects the carcass and air chamber; transmits braking and traction forces; improves road grip	Thickness typically 7-17 mm (passenger cars) and 14-32 mm (trucks)
Breaker (belt package)	Reinforces the tread-carcass connection and absorbs part of operational shocks	Requires high dynamic strength, low heat build-up, resistance up to ~120°C, good thermal conductivity
Carcass (cord plies)	Structural foundation of the tire; withstands the highest operational stresses	Multiple fabric/steel cord layers with alternating orientations; materials include polyamide, polyester, fiberglass, steel
Bead	Ensures secure fit on the rim; prevents air loss; transfers forces between tire and wheel	Steel wire reinforcements embedded in rubber compound
Sidewall	Protects the carcass against environmental degradation, abrasion, and external damage	Flexible rubber layer exposed to aging and mechanical impacts
Reinforcement layers (steel/fabric belts)	Increase tread rigidity, stabilize contact area, reduce deformation, improve handling	Steel wire plies form a ring under the tread; radial tires usually 1-2 layers, bias-ply may have more
Inner liner	Maintains airtightness and prevents air diffusion	Low-permeability rubber (bromobutyl or chlorobutyl)
Radial plies	Provide the main load-carrying structure and improve flexibility and ride comfort	Layers of steel cables or textile fibers arranged perpendicular (~90°) to the direction of travel, extending from bead to bead

Figure 4 illustrates the distribution of rolling resistance contributions among the primary tire components which provides a comprehensive overview of the mechanics underlying rolling resistance in pneumatic tires. The research highlights that more than 90% of total rolling resistance arises from the deformation of the tread area when it shifts from a circular shape to a flat contact patch with the road surface, resulting in considerable energy losses manifested as heat. Based on finite element simulations, the tread contributes around 50% of the rolling resistance, the sidewalls 10%, the casing and internal structural layers 20%, and the bead 20%. The results imply the most efficient technique to enhance rolling resistance is to reduce energy losses in the tread, albeit these percentages may vary depending on tire design. Therefore, a balanced approach that retains braking efficacy while boosting energy efficiency is essential [13, 18].

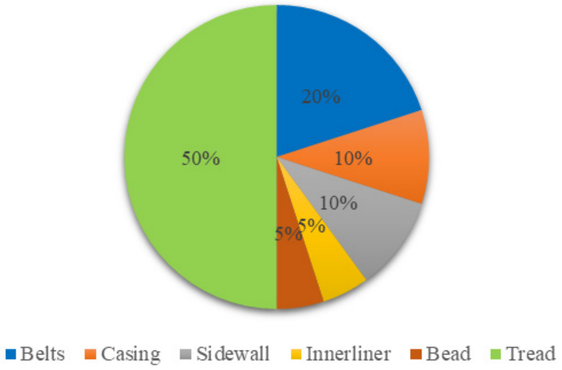


Figure 4. Rolling resistance contribution for passenger car [18].

2.2 Chemical Compounds of the Tire

Figure 5 illustrates a pie chart depicting the chemical makeup of a tire, emphasizing the quantities of different elements utilized in rubber compound production. This graphic is crucial for comprehending the intricacies of tire compound formulation, especially for the tread, and it underscores that the tire's ultimate performance derives from a meticulous and balanced selection of components employed.

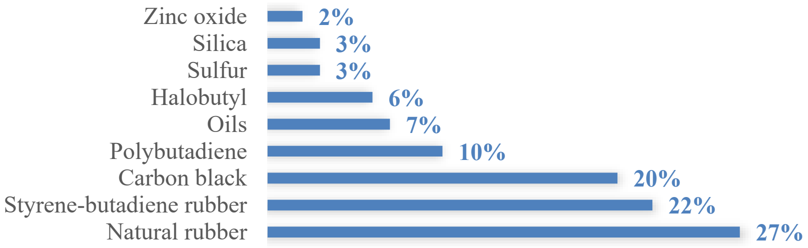


Figure 5. Distribution of key chemical components used in tire rubber formulations [8].

The following chemicals have been identified [1, 16, 19]:

- Because of its superior wear resistance, low-temperature adhesion, and ability to dissipate mechanical energy, natural rubber makes up a significant portion of the composition. It is essential for applications that call for resilience and adaptability;
- Styrene-butadiene rubber is a synthetic elastomer frequently utilized in tread formulations, is chosen for its excellent traction on both wet and dry surfaces and its durability against wear;
- Polybutadiene is utilized for its abrasion resistance and minimal hysteresis, which decreases rolling resistance and enhances fuel efficiency;
- Halobutyl is particularly significant in inner liner compounds because of its low air permeability and high chemical resistance;
- Carbon black, an essential filler material, imparts stiffness, wear resistance, UV protection, and aids in heat dissipation;

- Oils serve as plasticizers to enhance compound processability and modify hardness or flexibility;
- Silica, utilized in conjunction with coupling agents such as silanes, diminishes rolling resistance and enhances traction. It is progressively utilized in high-performance and environmentally sustainable tires;
- Sulfur is crucial in the vulcanization process, since it forms chemical bridges between polymer chains, thereby solidifying the rubber structure. Zinc oxide (ZnO) and stearic acid serve as activators in the vulcanization process, promoting the development of sulfur cross-links.

The hysteresis properties of the rubber materials used in the tire tread have the biggest effect on rolling resistance. The choice of filler materials, notably the amount of silica and carbon black, can have a big effect on rolling resistance [8, 20].

The study [20] looks at how partially replacing carbon black with precipitated silica in tread compounds for truck tires made from natural rubber (NR) and butadiene rubber (BR) affects the dynamic performance of tires. This provides insights into the trade-offs associated with silica addition in tread compound formulation. The results show that adding additional silica (up to 20 phr) improves the material’s resistance to fatigue, rolling resistance, and thermal dissipation. This indicates improved performance under dynamic operating conditions. At the same time, the lower crosslink density caused attributes including tensile strength, modulus, and wet grip to decrease. These trade-offs show that when choosing the type and amount of fillers, a balanced formulation needs to be ensured, so that it meets the needs for durability, energy efficiency, and road safety at the same time.

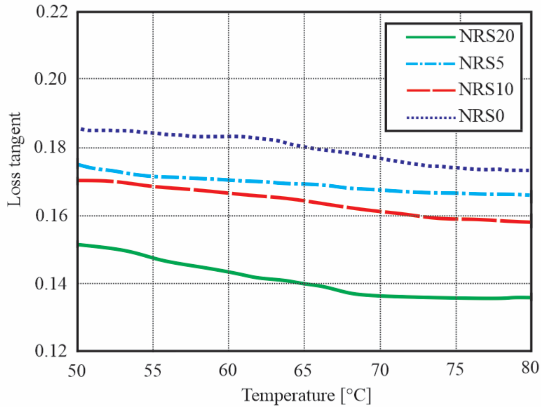


Figure 6. The temperature range that was used to test the rolling resistance [20].

Figure 6 illustrates how the loss tangent (tan δ), a viscoelastic parameter describing energy dissipation (hysteresis) in rubber, varies with temperature (50-80 °C) for rubber composites containing varied concentrations of silica and carbon black, a conventional reinforcing filler commonly used in tire compounds. This temperature range is important since it is the range in which tires exhibit rolling resistance. As the amount of silica in the rubber compound goes up from the NRS0 formulation (0% silica) to the NRS20 formulation (20% silica), the tan δ values decrease. This drop means that the tire’s rolling resistance has improved because it dissipates less energy through viscoelastic hysteresis. So, employing silica as a filler instead of carbon black makes the car more energy efficient by consuming less fuel. Partial substitution of carbon black with precipitated silica in natural rubber compounds significantly improves dynamic properties and reduces rolling resistance, without compromising mechanical or thermal performance. This significantly reduces rolling resistance, thus making silica-filled compounds highly suitable for green tire applications [20, 21].

The findings of the experiments show that the type of tire, the load circumstances, and the temperature outside all have a big effect on how much tire-road particulate matter is released. Tests on a climatic roller dynamometer showed that PM10 emissions were more than twice as high under predominantly lateral slip conditions (simulated cornering) compared to predominantly longitudinal slip conditions (simulated braking or traction), with an average of 5.1 mg/km per tire. The winter tire had the largest particle emissions of the three tested tire types, especially when it was cold. It had an average of 2.9 mg/km under longitudinal stress and 6.0 mg/km under lateral load. The all-season tire had average values of 2.1 mg/km in case of longitudinal forces acting on the wheel, 4.5 mg/km under lateral forces, while the summer tire was the best at reducing wear and particulate emissions (1.4 mg/km with longitudinal forces, 3.2 mg/km with lateral forces). These differences are due to the different viscoelastic behavior of the tread compounds and how sensitive they are to temperature. This shows how important it is to develop tread materials tailored for each season, which may reduce emissions without affecting the vehicle’s maneuverability [22, 23].

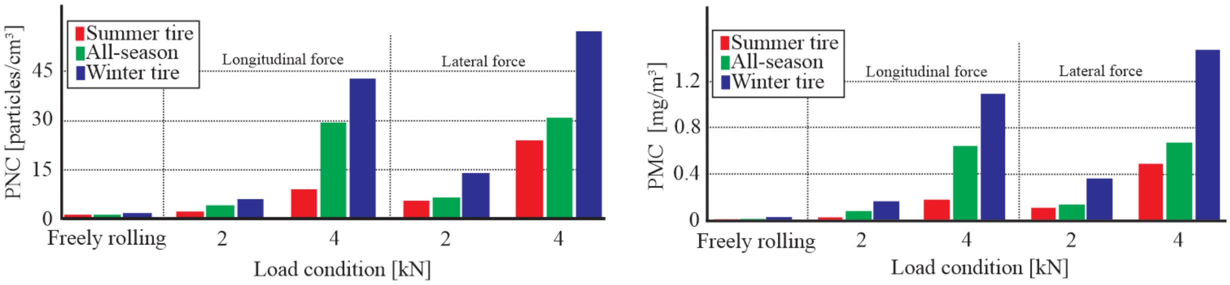
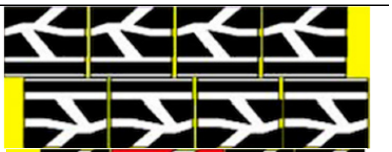
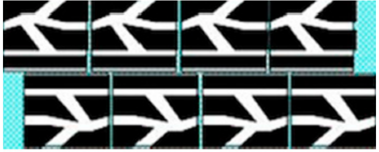
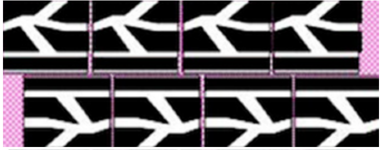
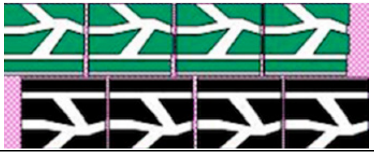


Figure 7. Influence of tire type on PMC and PNC for different load conditions. [22].

3. General Aspects of Tire Design

The outer surface of the tread, which is made up of a carefully planned network of grooves, is referred to as the tire's design. These grooves, sometimes referred to as tread blocks or figures, create geometric patterns on the tire surface [24].

Table 4. Classification of tread pitch randomization types and their geometrical arrangement [24]

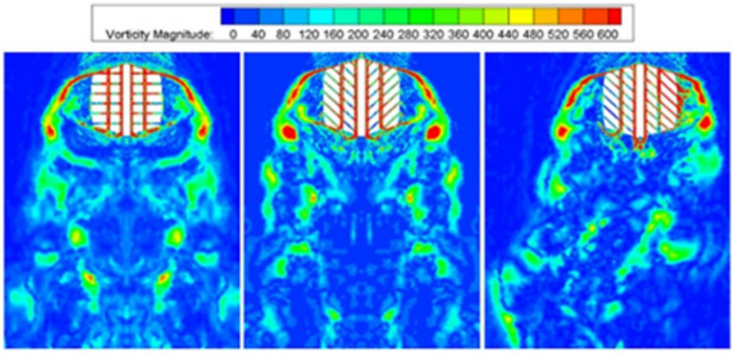
Classification criterion	Type	Description	Schematic representation
Randomization	Constant Pitch	All tread segments have identical length, indicating the absence of randomization	
	Synchronous	The segments vary in length, while their arrangement sequence remains identical on both sides of the tire	
	Asynchronous	The segment lengths are different, and their sequence is not the same on the two sides of the tire	
Symmetry	Symmetry	The tread segments are symmetrically arranged, with identical elements on both sides of the tire	
	Asymmetric	The tread pattern arrangement differs between the left and right sides	
Directionality	Bi-directional	The elements on one side are rotated by 180° relative to those positioned on the opposite side	
	Directional	The tread elements on one side represent mirrored counterparts of those on the opposite side	

The study [25] looked at three different types of tire tread patterns symmetrical, asymmetrical, and directional and compared them to which extent stones were trapped in the grooves and how that affected the performance of the tires. The results of the numerical simulations showed that various tread designs were very different from each other. For Von-Mises equivalent stress and total deformation (see Table 5), the asymmetrical tread pattern had the highest values for stone-trapped tires, which means that there was more mechanical stress and deformation. The directed tread pattern, on the other hand, had the lowest values for these characteristics, meaning that it was better able to handle the stresses caused by stones. When looking at wear under steady state rolling conditions, as shown by the maximum equivalent elastic strain, the symmetrical tread pattern showed the smallest increase in values due to stone trapping, both on dry and wet road surfaces, showing an increased durability of the tire. The authors conclude that the directional design is suitable for decreasing internal tensions, but the symmetrical pattern is better at resisting wear when there are stones, it would be the more recommended choice for different types of roads.

Table 5. Stress and deformation response of selected tread patterns in the presence and absence of trapped stones [25]

Tread pattern type	Without trapped stone		With trapped stone	
	Peak von Mises stress [MPa]	Deformation [m]	Peak von Mises stress [MPa]	Deformation [m]
Symmetrical	11.46	0.0345	15.01	0.1276
Asymmetrical	19.18	0.1434	24.83	0.3392
Directional	9.34	0.0745	13.97	0.1407

One important thing to be taken into consideration while designing tire tread patterns is how they affect the vehicle’s aerodynamics. Study [26] looked at how three tires with varied tread patterns, symmetric, asymmetric, and directional, behaved in the wind tunnel and through computational fluid dynamics (CFD) simulations. The results showed that directional (point-symmetric) tread patterns had the lowest levels of turbulent kinetic energy (TKE) and the least amount of airflow separation. This meant less aerodynamic drag and better efficiency. On the other hand, the asymmetric (axis-symmetric) tread design created big vortices and a big flow separation zone, which meant that the airflow was less stable, and the aerodynamic performance was lower. The symmetric tread pattern represented an intermediate solution between the two extremes, offering a balanced overall performance. These findings highlight the importance of selecting an appropriate tread design not only for grip and stability, but also for reducing rolling resistance and, consequently, fuel consumption.



a) Symmetric b) Directional c) Asymmetric

Figure 8. Time-averaged vorticity distributions in the analyzed section for three tire models [26].

Based on the vorticity distributions shown in Figure 8, it can be said that directed tread tires have the best aerodynamic properties among the three designs that were looked at. The low vorticity values and the orderly flow structure depicted in Figure 8 suggest that there isn’t much airflow separation, which means less aerodynamic drag. These properties make directional tires a good choice for high-speed driving, where flow stability and aerodynamic efficiency are very important for the overall vehicle’s stability and maneuverability.

Seasonally, tires fall into three broad groups: summer, winter, and all-season. Summer tires are designed for warm weather and dry or wet asphalt, with stiffer rubber compounds and fewer tread grooves. Winter tires are built of softer materials that remain flexible in cold weather and include deeper treads with sipes for enhanced traction on snow and ice. All-season tires offer year-round usability but often underperform specialty tires in extreme weather conditions. The variations between winter, summer, all-season, and ultra-high performance (UHP) tires are often studied in the specialized literature to see how they affect the dynamic performance of road vehicles. Research by [27] looked at how various tire types behaved in terms of cornering stiffness using a simplified single-track model that was tested on a sports vehicle to make sure it worked. The tests were done on the same proving ground, with the same track temperature of 25°C. This temperature is important because it highly influences how rubber compounds act, especially in winter tires, which tend to get stiffer in these conditions [3, 4, 28].

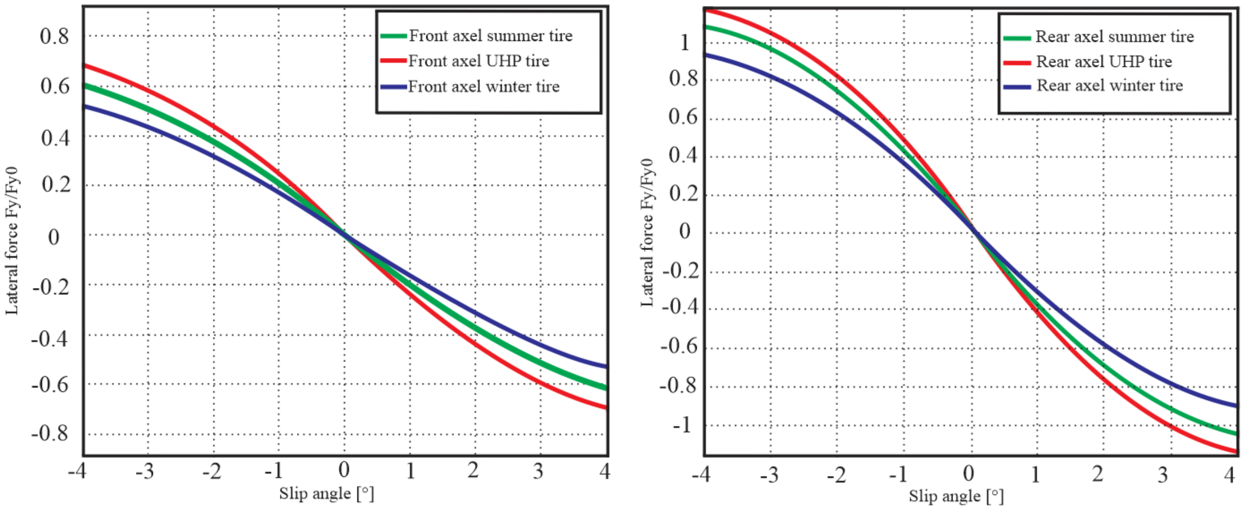


Figure 9. Variation of normalized axle lateral forces with axle sideslip angle for different tire types [27].

Figure 9 of the study shows the normalized lateral force curves for the three tire types as a function of slip angle. These curves show that the tires behave very differently while they are moving sideways. Table 6 shows that UHP tires had the greatest cornering stiffness values. When compared to summer tires, which were used as a reference, the front axle's cornering stiffness went up by around 16%, and the rear axle's cornering stiffness increased by about 13%. On the other hand, winter tires were less rigid, with a 12% drop at the front axle and a 17% drop at the rear axle. These changes had a direct effect on the vehicle's dynamic properties, namely its characteristic speed, yaw natural frequency, and damping factor.

Table 6. Effect of different tire setups and cornering stiffness changes on vehicle dynamic characteristics [27]

Dynamic parameter	Winter tire setup	Summer tire setup	UHP tire setup
Front axle cornering stiffness	-12%	baseline	+16%
Rear axle cornering stiffness	-17%	baseline	+13%
Characteristic speed	-2%	baseline	+9%
Natural yaw frequency	-14%	baseline	+10%
Damping ratio	-2%	baseline	+4%

As demonstrated in Figure 10, UHP tires increased the natural frequency by 10% and the damping by 4%. Here, ω_0 denotes the yaw natural frequency of the vehicle's lateral dynamics, while D represents the corresponding damping factor. This resulted in a faster and better-damped vehicle response, improving stability during short-term maneuvers. So, the study of different types of tires shows not only how they are made and what they are made of, but also how they affect the way a vehicle moves. These results reinforce the idea that the sort of tire one choose should not only depend on the weather, but also on how stable and easy to handle the vehicle must be for the foreseen application [27].

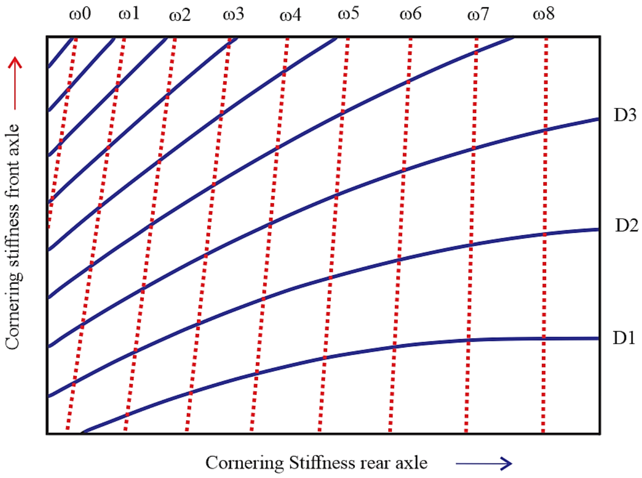


Figure 10. Axle cornering stiffnesses with different tire types [27].

The study [29] compared summer tires (Dunlop 245/40R19) with winter tires (Dunlop 245/45R18) and found that their dynamic behavior was very different, in the sense that summer tires had stronger cornering stiffness when tested on both dry and wet surfaces.

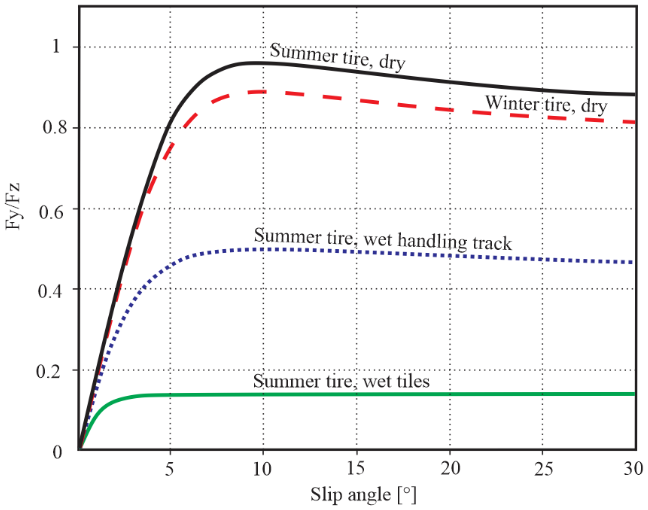


Figure 11. Comparison of the lateral behavior of summer and winter tires on dry and wet surfaces [29].

This made the handling more responsive and improved stability during transient cornering maneuvers (non-steady-state handling situations), especially on dry asphalt. Winter tires, on the other hand, were designed for cold and slippery weather, but they had less lateral stiffness, which made them respond more slowly and less accurately when turning sharply. Figure 11 illustrates these results and shows that summer tires on dry surfaces achieved the highest Fy/Fz values, indicating a superior ability to transmit lateral force. In contrast, winter tires exhibited considerably lower values, although they remained more predictable under low-traction conditions. Also, summer tires did far worse on wet surfaces (handling track and wet tiles), which shows how important it is to make tread design and compound formulation fit the conditions in which they would be used. These studies back up the idea that when choosing tires, not only should the season be taken into consideration, but also the predicted road conditions.

In the second case, Figure 12 shows how the adhesion coefficient (μ) varies with slip for two tire types (winter and summer) under various surface and temperature conditions. Tests were carried out on a dry surface at -15°C in the first case and on a wet surface at 32°C while maintaining a constant driving speed of 60km/h. It is evident that the summer tire works better in hotter climates and on damp surfaces, while the winter tire offers a higher adhesion coefficient in colder climates. This variation illustrates how well the rubber compounds unique to each tire type adapt to the temperature ranges for which they were intended. To optimize dynamic performance and operational safety, the data emphasized the importance of the tire's choice based on both season and road conditions [30].

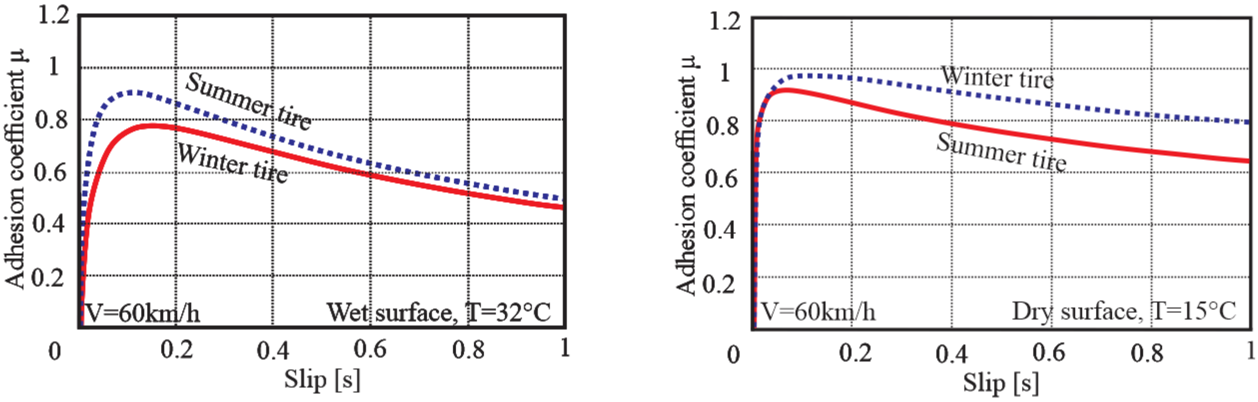


Figure 12. Variation of the friction coefficient (μ) with slip for summer and winter tires under different temperature and road surface conditions [30].

In study [31], rolling resistance was experimentally assessed for passenger car tires belonging to five categories under actual road operating conditions. The tests were carried out at a constant speed of 80 km/h on two worn road surfaces: DAC 16 (Dense Asphalt Concrete, with a maximum aggregate size of 16 mm) and SMA 8 (Stone Mastic Asphalt, with a maximum aggregate size of 8 mm). The rolling resistance force opposing tire motion was measured using a specially instrumented trailer. Figure 13 presents the rolling resistance coefficient (RRC, %) obtained for the five tire categories considered, namely all-season (AS), summer (SU), winter without studs (WI), winter with embedded hard particles (WIGD, also known as Green Diamond), and winter with studs (WIST). The columns indicate the mean RRC values, while the 95% confidence intervals were estimated through non-parametric bootstrapping for each tire specimen. Each point corresponds to an individual tire sample.

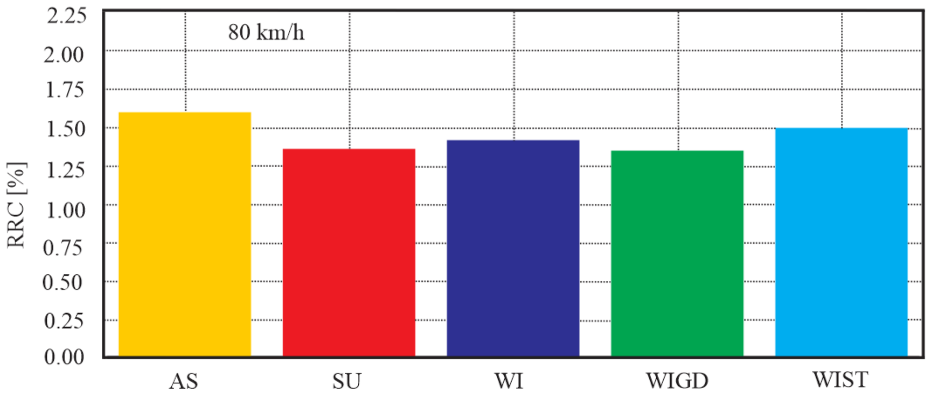


Figure 13. Rolling resistance coefficients [31].

The results showed that there was a considerable variation within each tire group, especially in the winter (WI) group. However, they also let us make some general conclusions. The all-season (AS) tires had the highest average RRC values, which suggests that their design for both warm and cold temperatures made them less energy efficient. In contrast, the WIGD tires had the lowest average rolling resistance, which shows that they could help save fuel and cut down on CO_2 emissions. This is even more true because they are made from retreadable materials that extend tire service life and reduce end-of-life waste, contributing to improved environmental sustainability. It was interesting to note that studded winter tires (WIST) did not always have higher rolling resistance than non-studded ones (WI), contrary to the presumption that studs contribute to energy losses. The authors [31] concluded that while the type of tire affects rolling resistance, the differences between specific models within the same category are even more important. They also emphasized that energy labeling rules should better reflect real-world testing conditions, since there was no strong link between RRC values found on the road and those given by the EU label system. Rolling resistance is primarily influenced by tread compound formulation, carcass structure, and inflation pressure. Improving energy efficiency requires a careful trade-off between minimizing energy loss and preserving safety-related performance, such as grip and directional stability [31, 32].

Braking distance represents a critical parameter of vehicle dynamic performance and is directly influenced by several tire characteristics, including tread design, inflation pressure, wear state, and material composition. Experimental studies have shown that the selected tire type significantly affects both vehicle control and deceleration performance in different operating environments. In one study involving four tire categories: new summer, worn summer, winter, and all-season tires, substantial variations in stopping distance were observed on both dry and wet asphalt. At 80 km/h on wet pavement, the stopping distance increased from 24.9 m for the new summer tire to 32.8 m for the winter tire, whereas the worn summer tire reached 29.6 m. These findings confirm that braking performance is influenced not only by tire category, but also by the degree of tire wear. The corresponding braking distance values for dry and wet surfaces are presented in Table 7. Therefore, the choice of tire type can affect fuel consumption and directional stability, while also playing an essential role in collision avoidance. From this perspective, intelligent tire technologies integrated into advanced braking systems such as ABS could help reduce uncertainty and improve braking control by accounting for the actual tire condition [33-35].

Table 7. Braking distance values for different tire types on dry and wet asphalt surfaces [35]

Tire type	Dry surface	Wet surface
New UHP tire	22 m	24.9 m
Winter tire	27.5 m	32.8 m
All-season tire	25.6 m	30.9 m
Worn summer tire	22.5 m	29.6 m

A recent study [36] investigated braking distances under various tire and environmental conditions using video analysis techniques. The researchers evaluated the braking capabilities of a Volvo S80 with both summer and winter tires on dry, wet, and snowy roads using the open-source Tracker software. Their findings showed that tire type and surface condition have a significant impact on braking distance, with summer tires on dry asphalt having the highest coefficient of friction ($\mu = 0.82$) and winter tires on snow having the lowest ($\mu = 0.28$). The data demonstrated that snow-covered roads considerably lengthen stopping distances even with winter tires, as shown in Figure 14, underscoring the importance of appropriate tire selection and driver education. This method also confirmed that video analysis is a trustworthy and user-friendly substitute for traditional measurement instruments.

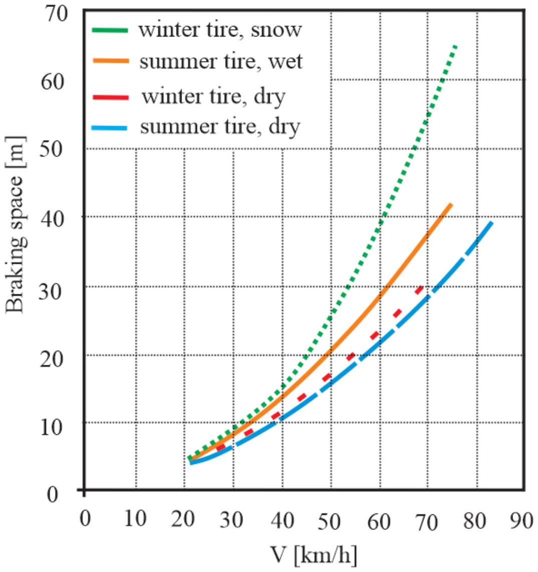


Figure 14. The braking distances using summer/winter tires on dry, wet, and snowy roads [36].

The tire's operating conditions, such as temperature, road surface conditions, and inflation pressure, have a significant impact on the Anti-lock Braking System's (ABS) performance. Changes in these parameters have a direct impact on the braking force coefficient, ABS control cycle time, and vehicle stability during braking maneuvers.

The authors of [36] reported that wet road surfaces and lower tire pressure considerably reduce ABS efficiency by lengthening braking distances and decreasing lateral stability. These results emphasize how important it is to choose the right tire type and maintain the prescribed tire inflation to guarantee road safety, particularly in situations involving severe braking.

Figure 15 shows how different tire operating parameters affect braking stiffness, defined as the slope of the tire longitudinal force–slip ratio curve measured around zero slip. The interaction of vertical load and inflation pressure on braking stiffness is depicted in Figure 15 (a), where higher loads led to increased stiffness at all pressure levels. The effect of tread wear is demonstrated in Figure 15 (b), which shows that worn tires have noticeably more braking stiffness than fully treaded tires, particularly when loads are higher. As the temperature rises, Figure 15 (c) shows a noticeable decrease in braking stiffness, with the effect being more noticeable at higher loads. The normalized braking stiffness of various tire constructions is finally compared in Figure 15 (d), which demonstrates that summer tires exhibit the highest stiffness and winter tires the lowest values. These results highlight how important tire design and operating conditions are to achieving the best possible braking performance, especially in ABS-equipped systems [37].

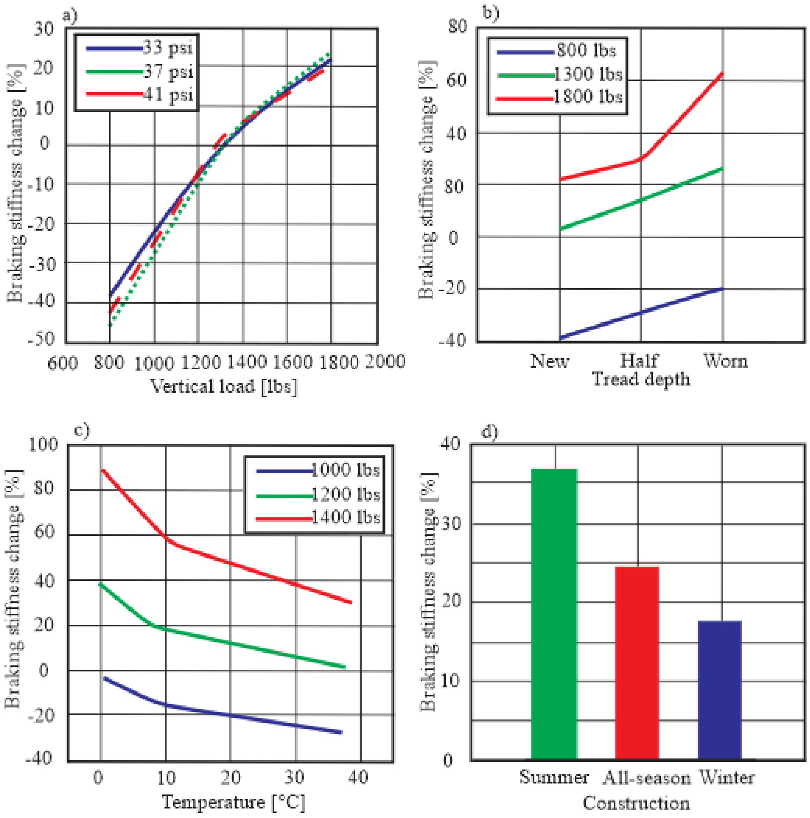


Figure 15. Influence of vertical load, tread depth, temperature, and tire construction on braking stiffness change relative to the nominal value [37].

4. Conclusion

The intricate and multifaceted connection between tire construction, design, and road vehicle dynamic performance is highlighted in this review. Vehicle handling, braking distance, rolling resistance, and energy efficiency are all greatly impacted by tire selection, as shown by the examination of several tire types of summer, winter, all-season, and UHP under various load and environmental circumstances. Traction, stability, and tire wear are all directly impacted by structural elements like tread pattern, carcass design, and chemical makeup. Furthermore, optimizing tread designs and incorporating sustainable materials like silica not only improves performance but also lessens their negative effects on the environment. The necessity of standardized tire labeling and selection systems that are adapted to climates and driving conditions is further highlighted by regional priorities and regulatory frameworks.

The detailed analysis of the specialized literature indicates that most experimental and numerical studies converge on the conclusion that tread pattern geometry, compound formulation, and carcass stiffness play a decisive role in force generation and vehicle stability. At the same time, the reviewed studies consistently highlight inherent trade-offs between safety-related performance, such as grip and braking stability, and energy efficiency, particularly in the case of low hysteresis and silica-filled compounds.

Finally, this paper emphasizes how crucial proactive maintenance and well-informed tire selection are to improving road safety and maximizing vehicle dynamics in practical situations. Based on the reviewed studies, future research directions include the integration of intelligent tire systems, real-time monitoring technologies, and advanced modeling approaches to better predict tire behavior under variable operating conditions and to reduce uncertainty in braking and handling performance.

5. Challenges and Perspectives

Despite the significant advancements in tire design and modern materials in recent years, several areas remain unclear and require further research. One of the main challenges is accurately describing tire–road interaction under real-world conditions. While experimental and numerical models can simulate certain driving scenarios, tire behavior becomes more complex in situations such as braking on wet or icy roads, combined longitudinal and lateral slip, or large temperature variations. Since the contact patch is where the primary traction and braking forces are generated, improving the prediction of friction and slip remains a crucial direction for future research.

Another key issue is finding the right balance between energy efficiency and safety. Lowering rolling resistance is essential for reducing fuel consumption and emissions, but optimizing tread compounds may sometimes compromise grip, particularly on low-friction surfaces. Therefore, the development of modern tires should aim to achieve a balance between minimizing energy losses and ensuring high traction and stability.

A promising direction for future research is the development of intelligent tires able to monitor, in real time, parameters including inflation pressure, temperature, wear level, and grip potential. These innovations may enhance the performance of modern active safety systems, including ABS and Electronic Stability Control (ESC), by enabling vehicle responses to be adjusted according to actual tire and road conditions.

References

[1] Kovac FJ, Rodgers MB. Tire Engineering. In: Mark JE, Erman B, Eirich FR, editors. Science and Technology of Rubber. 2nd ed. San Diego: Academic Press; 1994. p. 675-710. ISBN: 978-0124647862.

[2] Mohanta BS, Kumar A. A parametric analysis on the performance of vehicle tires. Mater Today: Proc. 2021; In press. doi: 10.1016/j.matpr.2021.03.167.

[3] Konečný V. All-season tires and their inappropriate selection due to the current economic shortage of raw materials. In: Proceedings of the 3rd International Conference CNDGS 2022 – Challenges to National Defense in a Contemporary Geopolitical Situation; 2022; Brno, Czech Republic. Brno: University of Defense; 2022. p. 32-40. doi: 10.47459/cndcgs.2022.4.

[4] Bhoopalam AK, Sandu C. Review of the state of the art in experimental studies and mathematical modeling of tire performance on ice. J Terramech. 2014;53:19-35. doi: 10.1016/j.jterra.2014.03.007.

[5] Voiku IP, Komissarov IA. Double-sided summer-winter vehicle tire: advantages and prospects of industrial production. IOP Conf Ser: Mater Sci Eng. 2020;709:022013. doi: 10.1088/1757-899X/709/2/022013.

[6] Han W, Han D, Chen H. Pyrolysis of waste tires: A review. Polymers. 2023;15:1604. doi: 10.3390/polym15071604.

[7] Li T. Influencing parameters on tire–pavement interaction noise: Review, experiments, and design considerations. Designs. 2018;2:38. doi: 10.3390/designs2040038.

[8] Rodgers B. Tire engineering: an introduction. Boca Raton (FL): CRC Press; 2021. ISBN: 978-0-367-44228-6.

[9] Khaleghian S, Emami A, Taheri S. A technical survey on tire-road friction estimation. Friction. 2017;5:123-46. doi: 10.1007/s40544-017-0151-0.

[10] Pauwelussen JP. Essentials of vehicle dynamics. Oxford: Butterworth-Heinemann (Elsevier); 2015. ISBN: 978-0-08-100036-6.

[11] Ptak W, Czarnecki J, Brennensthul M, Lejman K, Małecka A. Evaluation of tires acting on soil in field conditions using the 3D scanning method. Agriculture. 2023;13:1094. doi: 10.3390/agriculture13051094.

[12] He J, Liu Y, Ma L, Wang T. Investigation on tire–road friction characteristics considering temperature and sliding velocity. Appl Sci. 2022;12:10467. doi: 10.3390/app122010467.

[13] Bellinetto E, Ciapponi R, Contino M, Marano C, Turri S. Microalgal biomass as renewable biofiller in natural rubber compounds. Polym Bull. 2022;79:8927-46. doi: 10.1007/s00289-021-03935-z.

[14] Gong Z, Miao Y, Lantieri C. Review of research on tire–pavement contact behavior. Coatings. 2024;14:157. doi: 10.3390/coatings14020157.

[15] Zheng B, Huang X, Zhang W, Zhao R, Zhu S. Adhesion characteristics of tire-asphalt pavement interface. Adv Mater Sci. 2018; In press.

[16] Gao N, Wang F, Quan C, Santamaria L, Lopez G, Williams PT. Tire pyrolysis char: Processes, properties, upgrading and applications. Prog Energy Combust Sci. 2022;93:101022. doi: 10.1016/j.pecs.2022.101022.

[17] Wang Y, Cui Z, Wu J, Su B, Zhao J. An improved method of using equilibrium profile to design radial tires. J Adv Mech Des Syst Manuf. 2015;9:JAMDSM0018.

[18] Akutagawa K. Technology for reducing tire rolling resistance. Tribol Online. 2017; In press.

[19] Helexa M, Krilek J, Kováč J, Kuvik T, Mancel V, Abrahám R, et al. Comparison of radial ply and cross ply tire in terms of achieved rolling resistance and soil compaction in a soil test channel. Forests. 2024;15:1397. doi: 10.3390/f15081397.

[20] Song S, Choi H, Jeong J, Kim S, Kwon M, Kim M, et al. Optimized end functionality of silane-terminated liquid butadiene rubber for silica-filled rubber compounds. Polymers. 2023;15:2583. doi: 10.3390/polym15122583.

[21] Liang C, Li H, Mousavi H, Wang G, Yu K. Evaluation and improvement of tire rolling resistance and grip performance based on test and simulation. Adv Mech Eng. 2020;12:1687814020981173. doi: 10.1177/1687814020981173.

[22] Schläfle S, Unrau H-J, Gauterin F. Influence of load condition, tire type, and ambient temperature on the emission of tire–road particulate matter. Atmosphere. 2023;14:1095. doi: 10.3390/atmos14071095.

[23] Sadiktsis I, Bergvall C, Johansson C, Westerholm R. Automobile tires—A potential source of highly carcinogenic dibenzopyrenes to the environment. Environ Sci Technol. 2012;46:3326-34. doi: 10.1021/es204257d.

[24] Li T. Literature review of tire-pavement interaction noise and reduction approaches. J Vibroeng. 2018;20:2424-47. doi: 10.21595/jve.2018.19935.

[25] Zafarmehrabian R, Taghvaei Gangali S, Ghoreishy MHR, Davallu M. The effects of silica/carbon black ratio on the dynamic properties of the tread compounds in truck tires. E-J Chem. 2012;9:1102-12. doi: 10.1155/2012/571957.

[26] Gow JYE, Ku PX. The analysis of stone trapping in tire tread for various road conditions. MATEC Web Conf. 2021;335:03003. doi: 10.1051/matecconf/202133503003.

[27] Warth G, Frey M, Gauterin F. Usage of the cornering stiffness for an adaptive rear wheel steering feedforward control. IEEE Trans Veh Technol. 2019;68:1147-54. doi: 10.1109/TVT.2018.2883809.

[28] Neamțu G. The importance and role of tyres on road vehicles: their influence on braking distance. Int J Adv Multidiscip Res Stud. 2024;4:1088-101. doi: 10.62225/2583049X.2024.4.4.3156.

[29] Zhou H, Jiang Z, Wang G, Zhang S. Aerodynamic characteristics of isolated loaded tires with different tread patterns: experiment and simulation. Chin J Mech Eng. 2021;34:96. doi: 10.1186/s10033-021-00620-0.

[30] Pokorski J, Sar H, Reński A. Influence of exploitation conditions on anti-skid properties of tyres. Transport. 2019;34:415-24. doi: 10.3846/transport.2019.10426.

[31] Vieira T, Sandberg U, Erlingsson S. Rolling resistance evaluation of winter tyres on in-service road surfaces. Tire Sci Technol. 2017;45:171-96. doi: 10.2346/tire.17.450303.

[32] Bechtloff J, Koenig L, Isermann R. Cornering stiffness and sideslip angle estimation for integrated vehicle dynamics control. IFAC-PapersOnLine. 2016;49:297-304. doi: 10.1016/j.ifacol.2016.08.045.

[33] Stokłosa J, Bartnik M. Influence of tire pressure on the vehicle braking distance. Arch Automot Eng. 2022;97:60-73. doi: 10.14669/AM/155136.

[34] Mangal S, Ghosh P, Narasimha Rao KV, Mukhopadhyay R. Variable modulus approach to optimize tire rolling resistance. Tire Sci Technol. 2019;47:245-66. doi: 10.2346/tire.19.180200.

[35] Alamdari SAS, Wouters R, Tielman Y, Schaefer-O'Reilly S, Singh KB. Anti-lock brake system (ABS) enhancement with intelligent tires. In: Proceedings of the FISITA World Mobility Conference; 2024; In press. doi: 10.3850/FISITA2024-ABS-Enhancement.

[36] Hockicko K, Hockicko P, Ondruš J. Prospective use of the video analysis method in braking path investigation. Rom Rep Phys. 2025; In press.

[37] Sivaramakrishnan S, Singh KB, Lee P. Influence of tire operating conditions on ABS performance. Tire Sci Technol. 2015;43:216-41. doi: 10.2346/tire.15.430302.