



The Progress of Vehicles on Wet Roads

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Abstract. This paper explores hydrodynamic effects on cars in wet-road conditions and anti-skid strategies, focusing on tire tread designs. Wet roads pose safety risks due to reduced tire-road friction from water films. The paper analyses six tire tread patterns: longitudinal, transverse, combined, block, asymmetric, and directional. Each pattern's structure, working principle, and application in different environments are discussed. Longitudinal and directional patterns efficiently drain water at high speeds, reducing hydroplaning. Block and asymmetric patterns enhance traction on snow/ice through mechanical interlock and flexible materials. Transverse and deep-block patterns suit off-road/muddy terrains for grip on loose surfaces. The Reynolds lubrication equation and CFD methods like RANS, LES, and VOF provide theoretical tools for modelling water film pressure. Practical design cases show cost-effective, extreme-weather, and vehicle-type-specific optimisations. Findings improve understanding of wet-road friction and offer insights for safer family car designs. Future research may focus on advanced fluid-structure models, innovative materials, and intelligent control systems for better anti-skid technologies.

Keywords: Hydrodynamic Effects, Anti - Skid Strategies, Tire Tread Designs, Wet - Road Condition.

1 Introduction

The automotive industry's relentless pursuit of enhanced performance, safety, and sustainability has spurred significant advancements in automobile design. However, when operating on wet roads, they encounter significant challenges due to the interaction between the vehicle and the fluid (water film) on the road surface [1]. The presence of the water film on wet roads leads to a series of issues for cars. For instance, it decreases the tire-road friction, which in turn reduces the vehicle's driving performance and handling stability [2,3]. Such situations jeopardise people's safety. Thus, understanding the hydrodynamic effects on cars in wet-road conditions is of great engineering significance. It enhances the handling of automobiles on wet roads and offers valuable insights for the design of how family cars navigate such surfaces. The design of high-performance cars can be optimised based on hydrodynamic principles. Effective strategies can be identified through this process. Enhancing tire

tread patterns improves water traction [4,5]. Adjusting the chassis structure reduces the impact of water resistance [6]. These findings can then be applied to the development of family cars, improving their safety and performance when driving on wet roads. The development of research on automobiles in wet-road or snow-covered road weather conditions has gradually evolved. It changes from improving the overall structure of the vehicle to the interactions between the vehicle and the fluid on wet roads, with the deepening comprehension of fluid mechanics. This paper will compare and summarise the advantages and differences of various anti-skid methods developed over time. By doing so, it aims to distil the most effective strategies and provide a comprehensive understanding of how far the research has come, which will serve as a solid foundation for future advancements in this field. Also, this paper will look towards the future, predicting potential research directions and technological advancements in this area. This paper hopes to provide valuable insights for future research and progression in the field of automotive anti-skid.

2 Principles of Hydrodynamics and Calculation Methods

Firstly, when a car moves on a wet road, the water film on the road surface leads to complex hydrodynamic effects. The key hydrodynamic formula is the Reynolds equation for lubrication:

$$\partial_x \partial (12\mu h^3 \partial_x \partial p) + \partial_y \partial (12\mu h^3 \partial_y \partial p) = 2U \partial_x \partial h + V \partial_y \partial h + \partial t \partial h \quad (1)$$

Here, h represents the thickness of the water film, μ is the dynamic viscosity of water, p is the pressure in the water film, and U , V are the velocities of the car in the x and y directions, respectively. This equation illustrates the pressure distribution in the water film. For remote-controlled cars, a lower water film pressure means less upward force on the tires, which is beneficial for maintaining tire-road contact and friction. Through this formula, it becomes possible to optimise the design of the car to reduce the negative impact of the water film, such as through tire and chassis design. Secondly, in the hydrodynamic calculations about remotely controlled cars on wet surfaces, the computational fluid dynamics (CFD) simulation method plays a key role.

The hydrodynamic model based on the Navier-Stokes equations provides a theoretical foundation for analysing the flow field characteristics on wet surfaces. In practical applications, the RANS (Reynolds-Averaged Navier-Stokes) method has an advantage in computational efficiency when dealing with average flow fields, making it suitable for predicting the average characteristics of flow fields over long time scales. LES (Large Eddy Simulation), however, directly solves larger-scale eddies and captures transient flow-field information more meticulously, though at a relatively higher computational cost. VOF (Volume of Fluid) stands out in tracking the free surface of the water film and analysing its thickness distribution. By comparing these methods, researchers can select a more appropriate approach based on research goals and resource constraints. This enables accurate numerical simulation and stability analysis of fluid behaviour on wet surfaces.

3 Tire Anti-slip Strategies

Tire tread patterns are critical for maintaining traction and preventing slipping, especially in wet, rainy, or icy conditions. Different patterns are designed to optimise water evacuation, enhance contact with the road, and adapt to specific environmental challenges. Here is a more detailed introduction.

3.1 Six Types of Tread Patterns

Longitudinal Tread Patterns. Continuous longitudinal grooves parallel to the tire's rotation direction, as shown in Figure 1.

High-Speed Water Drainage: Longitudinal grooves act as streamlined channels that rapidly evacuate water at high speeds. As the tire rolls, centrifugal force and forward motion direct water along the grooves toward the shoulder, minimising water film accumulation between the tread and road. Research [7] highlights that deeper and wider longitudinal grooves reduce hydrodynamic lift by increasing water displacement volume, therefore raising the critical hydroplaning speed. This design prevents the tire from floating on water by efficiently breaking the water film, as evidenced by reduced static pressure in the contact area during wet-road simulations [8].

Lateral Stability Optimisation: The high longitudinal stiffness and low transverse stiffness of longitudinal patterns resist lateral slippage. Uniform contact pressure from central longitudinal blocks ensures consistent rubber-road engagement on wet surfaces, reducing the risk of sideslip by maintaining stable tire dynamics [7].

Highways and well-paved roads, particularly used on passenger car front tires, are designed to balance high-speed handling and efficient water drainage.



Fig. 1. The schematic illustration of longitudinal tread patterns. Reproduced with permission Ref. [7]. Copyright 2022 Wiley-VCH GmbH.

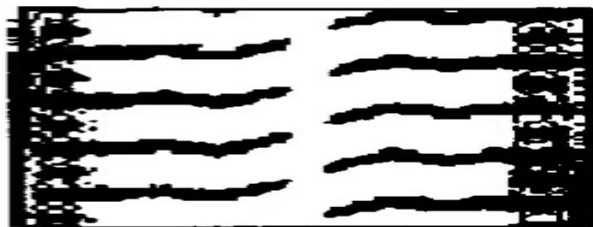


Fig. 2. The schematic illustration of transverse (lateral) tread patterns. Reproduced with permission Ref. [7]. Copyright 2022 Wiley-VCH GmbH.

Transverse (Lateral) Tread Pattern. Continuous transverse grooves perpendicular to the rotation direction of the tire, creating rigid rubber blocks (Figure 2).

Mechanical Interlock for Traction: Transverse grooves segment the tread into large rubber blocks that dig into uneven terrains like gravel or snow, generating robust longitudinal friction for acceleration and braking. This mechanical interlock is critical in low-adhesion environments, where the blocks engage with surface irregularities to enhance grip [8].

Trade-off in Wet Performance: While deep transverse grooves improve off-road traction, their discontinuous longitudinal structure limits high-speed water evacuation. Water can accumulate between blocks at high speeds, increasing hydroplaning risks, which is why these patterns are often paired with supplementary designs (e.g., combined patterns) for wet-road use [9].

Harsh off-road environments (mining, agriculture) commonly on truck wheels to maximise traction on loose or muddy surfaces.

Combined Tread Patterns. Central longitudinal grooves paired with lateral or block patterns on the shoulder, as shown in Figure 3.

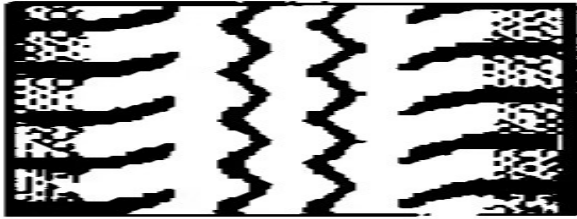


Fig. 3. The schematic illustration of combined tread patterns. Reproduced with permission Ref. [7]. Copyright 2022 Wiley-VCH GmbH.

Balanced Performance Design: The central longitudinal grooves inherit the high-speed water drainage capability of longitudinal patterns, efficiently channelling water away from the contact patch to reduce hydroplaning risk. Meanwhile, the shoulder-mounted transverse or block elements enhance lateral grip during cornering, addressing the trade-off between wet-road stability and dry-road traction. This hybrid structure ensures that water is rapidly evacuated while maintaining robust contact with the road under lateral loads [10]. By integrating different groove orientations, combined patterns optimise contact pressure across the tread. The central longitudinal zones reduce pressure concentration, while shoulder patterns increase stiffness during turns, balancing wear resistance and handling performance across diverse road conditions [10].

Mixed road conditions (urban and rural roads), widely used in trucks and buses to balance efficient water drainage and reliable traction in moderate wet or dry environments.

Block Tread Patterns. Independent, large rubber blocks separated by deep, interconnected grooves (Figure 4).

Ice/Snow Specific Mechanism: Block patterns are designed to break through compacted snow and ice by leveraging the sharp edges of individual blocks, which bite into the surface to create mechanical interlock. The deep grooves between blocks expel slush and prevent snow from packing into a smooth layer, maintaining direct rubber-to-ice contact. Additionally, fine sipes (slits within blocks) enhance flexibility at low temperatures, allowing the blocks to conform to micro-roughness and increase friction [7, 11].



Fig. 4. The schematic illustration of block tread patterns. Reproduced with permission Ref. [7]. Copyright 2022 Wiley-VCH GmbH.

The aggressive block structure increases contact pressure on icy surfaces, improving braking and acceleration performance in extreme cold. This design is critical for winter tires, where maintaining grip on low-adhesion surfaces is paramount [11].

Snowy and muddy roads commonly require winter tires to optimise traction through mechanical engagement and efficient snow evacuation.

Asymmetric Tread Patterns. Non-mirroring designs on inner and outer shoulders: the outer shoulder features wider, stiffer rubber blocks, while the inner shoulder incorporates dense, narrow grooves, as demonstrated in Figure 5.

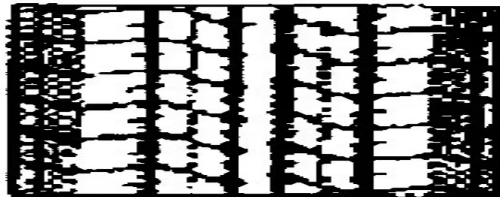


Fig. 5. The schematic illustration of asymmetric tread patterns. Reproduced with permission Ref. [7]. Copyright 2022 Wiley-VCH GmbH.

Dual-Function Zoning: The outer shoulder's rigid blocks are engineered to handle high lateral loads during cornering, increasing contact pressure to enhance dry-road grip and stability. In contrast, the inner shoulder's intricate groove network prioritises water evacuation, reducing hydroplaning risks on wet surfaces by rapidly channelling water away from the contact patch [7, 12].

During high-speed manoeuvres, the asymmetric design compensates for the natural load transfer to the outer tire, ensuring the stiffer outer blocks maintain robust lateral contact while the inner grooves efficiently drain water. This dual functionality minimises sideslip in turns and balances performance across dry and wet conditions [12]. High-performance vehicles and racing cars require strict directional installation (outer side outwards) to optimise high-speed cornering and wet-weather stability.

Directional Tread Patterns. Unidirectional “V” or “Y” shaped grooves aligned in a single forward direction, creating a streamlined drainage pattern (Figure 6).

Unidirectional Water Channelling: Directional grooves are angled to act as efficient flow guides, leveraging tire rotation to accelerate water evacuation from the contact patch. This design minimises water film accumulation, particularly at high speeds, by directing water longitudinally toward the tire's shoulder, reducing hydrodynamic lift and increasing the critical hydroplaning speed [7, 13].

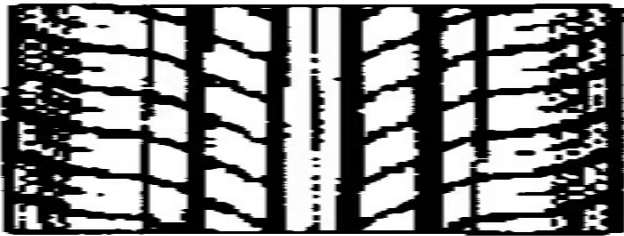


Fig. 6. The schematic illustration of directional tread patterns. Reproduced with permission Ref. [7]. Copyright 2022 Wiley-VCH GmbH.

The continuous, forward-aligned grooves enhance longitudinal stiffness, reducing tread deformation during high-speed travel. This rigidity maintains consistent contact with the road, improving straight-line stability in heavy rain, though reverse driving or sharp turns may compromise drainage efficiency due to the directional design [13].

High-speed wet roads, commonly used on passenger car tires for superior straight-line hydroplaning resistance and consistent braking performance in rainy conditions.

3.2 Comparative Analysis of Tread Patterns for Different Conditions

Wet and Rainy Roads. Longitudinal and directional patterns are most effective here. Longitudinal grooves quickly drain water, while directional designs enhance water

evacuation at high speeds, where increasing groove depth and width elevates hydroplaning resistance [8]. These patterns minimise water buildup, ensuring consistent contact and reducing skidding risks during braking or acceleration.

Snow and Ice. Block and asymmetric patterns dominate in snowy conditions. Block patterns independent rubber blocks bite into snow, while specialised rubber compounds (e.g. silica-rich blends) remain flexible in low temperatures, maintaining contact with icy surfaces [14]. Asymmetric designs, with their aggressive outer blocks, also improve traction during turns on snow-covered roads [15].

Mud and Off-Road Environments. Lateral and deep-block patterns are preferred. Lateral grooves dig into soft ground, providing pulling power, while deep blocks resist packing with mud, providing continuous grip. However, these patterns may struggle on paved wet roads due to reduced water drainage compared to longitudinal designs [8].

High-Speed and Dry Roads. Asymmetric and combined patterns offer the best balance here. Asymmetric designs enhance cornering stability with stiff outer blocks, while combined patterns ensure moderate water drainage for unexpected wet patches [16].

4 Optimization Design Cases of tires of Cars on Wet Roads

4.1 Cost-Effective Strategies for Budget Constraints

When financial resources are limited, a balanced approach integrating tire tread optimisation and pragmatic design ensures cost-effective anti-slip performance. Combined tread patterns, which merge longitudinal and lateral grooves, offer a practical solution through inheriting the high-speed water drainage capability of longitudinal channels and the moderate wet-road traction of lateral elements [9, 10]. Longitudinal grooves efficiently evacuate water to reduce hydroplaning risks, while lateral structures enhance rubber-road contact on non-extreme wet surfaces. It can avoid the complexity and cost of specialised high-performance patterns [7]. This design balances manufacturing affordability with functional performance, aligning with the engineering goal of optimising tire-road friction under constrained budgets [4, 5].

4.2 Environment-Specific Design for Extreme Weather

Snow and Ice Conditions. In low-temperature environments, block tread patterns with deep, independent rubber blocks and silica-rich compounds are critical for maintaining traction [7, 11]. The sharp edges of these blocks bite into compacted

snow and ice to create mechanical interlock, while the elastic properties of silica blends ensure rubber flexibility at sub-zero temperatures, maximising surface contact [11]. Such designs are validated by research on winter tire mechanics and demonstrate ideal grip through both structural engagement and material adaptation to icy surfaces [14].

High-Speed Wet Scenarios. For heavy rain or high-speed wet-road conditions, directional “V” or “Y” tread patterns leverage unidirectional groove alignment to accelerate water evacuation from the contact patch [7, 13]. The streamlined geometry directs water longitudinally toward the tire shoulder, reducing hydrodynamic lift and increasing the critical hydroplaning speed; a mechanism supported by computational fluid dynamics (CFD) simulations of water film pressure distribution [8]. This design prioritises straight-line stability and rapid drainage.

4.3 Vehicle-Type Specific Optimisation

Speed-Oriented Vehicles. High-performance and racing cars rely on asymmetric tread patterns to balance dry-road cornering stability and wet-road drainage [7, 12]. The stiff outer shoulder blocks enhance lateral grip during high-speed manoeuvres, while dense inner grooves efficiently channel water, minimising hydroplaning risks during aggressive turns [12]. This dual-function design is corroborated by research on tire kinematics, which shows that asymmetric structures compensate for load transfer and maintain optimal contact pressure under dynamic loads [16-18].

Off-Road Vehicles. For climbing or off-road applications, lateral and deep-block tread patterns are essential for traction in soft, muddy, or gravelly terrain [8]. Transverse grooves and robust rubber blocks dig into uneven surfaces, generating mechanical interlock to overcome low-adhesion environments, as demonstrated in studies on off-road tire mechanics [8]. These patterns prioritise material engagement over high-speed drainage, a trade-off validated by their effectiveness in rugged conditions where maintaining grip on loose substrates is paramount [9].

5 Conclusion

This paper delves into hydrodynamic effects and anti-skid strategies for cars navigating wet roads, focusing on tire tread designs and their interaction with road-surface water films. Through analysing longitudinal, transverse, combined, block, asymmetric, and directional tread patterns, their distinct advantages in water evacuation, traction, and environmental adaptability are identified. Longitudinal and directional patterns excel in high-speed wet conditions by efficiently draining water to reduce hydroplaning. Block and asymmetric designs dominate icy/snowy environments through mechanical interlock and material flexibility, while transverse and deep-block patterns suit off-road/muddy terrains by enhancing grip on loose

surfaces. Theoretical foundations, including the Reynolds lubrication equation and CFD simulation methods like RANS, LES, and VOF, provide tools to model water film pressure distribution and optimise tire-chassis interactions.

Practical design cases demonstrate that cost-effective solutions (e.g., combined patterns), extreme-weather adaptations (silica-rich compounds in block patterns), and vehicle-type-specific optimisations (asymmetric designs for high-performance cars) effectively balance performance and resource constraints. These findings not only improve understanding of tire-road friction under wet conditions but also offer actionable insights for enhancing family car safety and handling on slippery surfaces. Future research could explore advanced fluid-structure interaction models, innovative rubber materials for diverse temperatures, and intelligent control systems to further integrate tire dynamics with real-time road condition feedback, driving progress toward more reliable anti-skid technologies.

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