WEATHERSAFE

SAFETY ENHANCEMENT UNDER ADVERSE WEATHER CONDITIONS THROUGH IMPROVED ADAS/AD ROBUSTNESS

Deliverable D3.4

Safety on wet roads: impact of the friction estimation

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EXECUTIVE SUMMARY

This deliverable explores the crucial role of tire-road friction in vehicle safety, especially under wet weather conditions. As friction directly affects a vehicle's capacity to maneuver, stop, and remain stable, its reduction due to water, ice, or contaminants significantly increases crash risk.

Through a review of international accidentology data and scientific literature, the report confirms a strong correlation between reduced pavement friction and increased accident rates in adverse weather.

The document presents technical insights into pavement friction mechanisms—including longitudinal and lateral forces, slip dynamics, and the combined effects of braking and cornering. The two primary friction components—adhesion and hysteresis—are discussed in detail, with an emphasis on how pavement texture, tire properties, vehicle behavior, and environmental conditions affect them.

Furthermore, the report highlights the importance of friction estimation in modern vehicle control systems. Advanced Driver Assistance Systems (ADAS), Anti-lock Braking Systems (ABS), Electronic Stability Control (ESC), and autonomous driving technologies depend on accurate, real-time assessments of tire-road friction. Various sensing, AI-based, and connected-vehicle approaches for monitoring adherence are outlined.

Ultimately, the deliverable underscores the necessity of improving pavement conditions and implementing advanced friction estimation technologies to reduce accident rates and enhance road safety in wet environments.

REVISION HISTORY

Revision	Date	Description, updates and changes	Status
1.0	03/03/2025	First draft version, open for discussion	Draft
2.0	04/07/2025	Finalized version, ready for diffusion	Draft
3.0	01/10/2025	Update with feedback from Michelin	Draft
4.0	28/04/2026	Final version after Final Event	Approved

ABBREVIATIONS

ABS	Anti-lock Braking System
ADAS	Advanced Driver-Assistance Systems
AEB	Autonomous Emergency Braking
Ca (C alpha)	Cornering stiffness
ESC	Electronic Stability Control
F	Tangential friction force
FB	Braking slip force
FR	Rolling resistance force
Fy	Lateral force
Fx	Longitudinal force
μ (Mu)	Coefficient of friction
μx	Longitudinal friction coefficient
N	Normal (vertical) force
S	Slip speed
SR	Slip ratio
SFC	Sideway Force Coefficient
SN40R	Skid Number at 40 mph (with Ribbed tire)
V	Vehicle speed
Vp	Peripheral speed of the tire
r	Radius of the tire
ω (omega)	Angular velocity of the tire
V2X	Vehicle-to-Everything communication
WFT	Water Film Thickness

TABLE OF CONTENTS

EXECUTIVE SUMMARY 2
REVISION HISTORY 3
ABBREVIATIONS 4
TABLE OF CONTENTS 5
1. INTRODUCTION 6
2. ACCIDENTOLOGY ASSESSMENT WITH WET GRIP 6
3. PAVEMENT FRICTION AND SURFACE TEXTURE 9
4. CONCLUSION 23
5. ACKNOWLEDGEMENTS 24
6. REFERENCES 25
7. TABLE OF ILLUSTRATIONS 26

1. Introduction

The starting point for the design of any vehicle must be the point at which it interfaces with the environment in which it will move. All the forces that propel, stop and turn a vehicle are generated at the point where the tyre touches the ground. It is therefore important to understand what happens at this interface and to the tyre when it is under load.
In addition, multiple studies have shown an increment of the accidentology when this interface presents some changes in the adherence.
Goal of this deliverable is to present an overview of the impact that friction may have on the overall vehicle dynamics and how it could be possible to reduce accidentology in adverse weather conditions.

2. Accidentology assessment with wet grip

Safety is often defined in two ways—the quality or condition of being safe (i.e., freedom from danger, injury, or damage) or any of certain devices or actions designed to prevent a crash from happening. Thus, it stands to reason that highway safety can be characterized as a driving environment free from danger or, more appropriately, one that is operated with rules and features designed to minimize crashes and the associated consequences (fatalities, injuries, economic loss) (Transportation Research Board & National Academies of Sciences, Engineering, and Medicine, 2009)
Since the early years of motor vehicle transportation, governmental agencies and industry groups have worked continuously to institute highway safety measures. Over the past few decades, however, the societal demand for mobility and economic growth has increased, resulting in spiraling rates of vehicle travel and unprecedented levels of risk for highway users. Highway crashes are complex events that are the result of one or more contributing factors. Such factors fall under three main categories:

- driver-related
- vehicle-related
- highway condition related.

Of these three categories, highway agencies can control only highway conditions. This can be done by developing and administering effective design, construction, maintenance, and management practices and policies (Noyce, 2005).
Although most highway crashes involve multiple causative factors, crash investigations have consistently shown a link between crashes and pavement surface conditions / characteristics, such as friction and texture. Thus, there is a need for in-depth knowledge and understanding of the relationship between the two.
Highway crash investigations indicate a strong link between pavement surface condition - especially friction and texture - and crash rates. While quantifying the exact relationship between wet-weather crashes and pavement friction is challenging, research consistently shows that crash rates increase as pavement friction decreases, assuming other factors remain constant. Several studies over all the word support this conclusion.

In early 1960s, (McCullough, 1966) examined 571 sites in Texas and showed that **crashes were more frequent on low-friction pavements**. They recommended a minimum friction coefficient of 0.40 at 48 kph to reduce crash risks. This value has been proposed as a convenient value close to the point where the slope of crash rate versus friction decreased significantly.
Later on, in 1970s, some studies analyzed rural highways in Kentucky and found higher wet crash rates when pavement friction values SN40R (skid/friction number determined with a locked-wheel friction tester operated at 64 kph were below 40 (Rizenbergs, 1972).

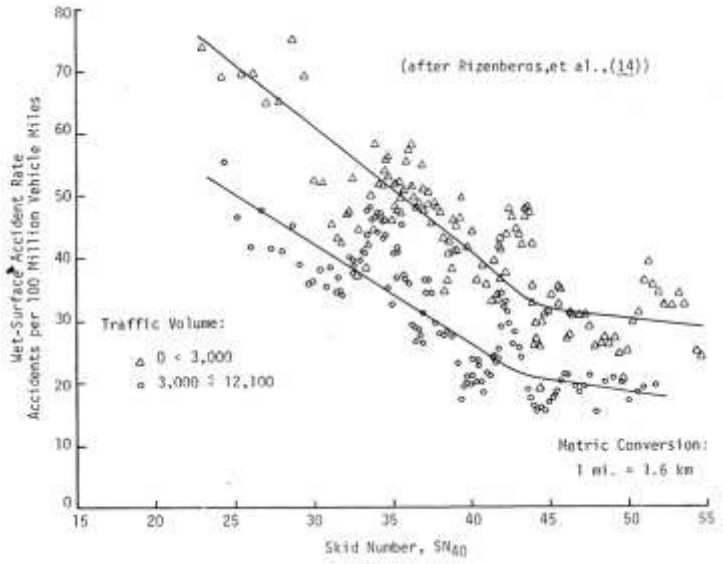


Figure 2-1Relationship between wet-weather crash rates and pavement friction for Kentucky highways (Rizenbergs, 1972)

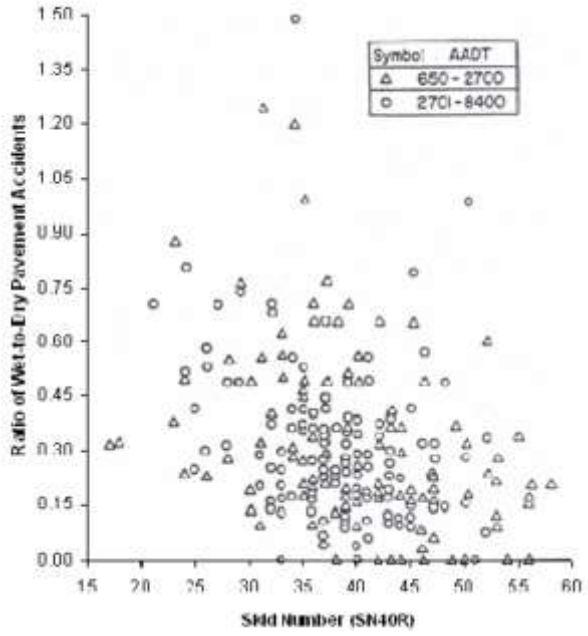


Figure 2-2 Ratio of wet-to-dry pavement crashes versus pavement friction for Kentucky highways (Rizenbergs, 1972)

Most recently, (Cairney, 1997) re-assested 20 crash sites and found that skid-related crashes were rare when friction values exceeded 60 but increased significantly when friction dropped below 50, as already proven by (Giles, 1962).

Overall accidentology studies confirm that the risk of crashes rises as wet pavement grip decreases. Research consistently shows also that **increasing pavement friction through resurfacing** significantly reduces crash rates, especially in wet conditions. Key findings from multiple studies include:

- (Miller, 1973) and (Cairney P. , 1997) showed that resurfacing the M4 highway in England increased pavement friction from 0.40 to 0.55, leading to a 28% reduction in dry crashes, 63% in wet crashes, and 45% overall total crashes.

- Works in (Kamel, 1982) has shown that resurfacing hazardous sections in Ontario reduced crashes by 46% at intersections (21% dry, 71% wet) and 29% on freeways (16% dry, 54% wet).
- In (Gothie, 1996), it has been proven that crash rates increased by 50% when moving from high-friction (Sideway Force Coefficient - SFC > 0.60) to low-friction (SFC < 0.50) sections. For a reduction in SFC of 0.05, the risk and severity of crashes increased by approximately 50%.
- In (Wallman, 2001) a comprehensive evaluation of friction measurements and crash rates revealed that increasing pavement friction does reduce crash rates significantly, as summarized in the table below:

Friction Interval	Crash rate (injuries per million vehicle km)
< 0.15	0.80
0.15 – 0.24 (ice)	0.55
0.25 – 0.35 (snow)	0.25
0.35 – 0.44 (wet)	0.20

Table 2-1 Relation between friction and crash rate (Wallman, 2001)

Studies worldwide confirm a strong **relationship between pavement friction and crash rates**, particularly in wet conditions. Key findings include

- the study (Gandhi, 1991), that found a significant correlation between minimum pavement friction and wet-to-dry crash ratios, with an R^2 value of 0.55. Minimum friction had a stronger impact on crashes than average friction.
- the French study (Larson, 1999), that showed found a five-fold increase in wet crash rates on the Bordeaux Ring Road when SFC dropped from above 0.60 to below 0.50. Crash risk also increased significantly when surface texture depth was below 0.40 mm.

These findings reinforce that improving pavement friction is a crucial factor in reducing wet-weather crashes.
For a deeper overview of existing literature on this point, please refer to (Transportation Research Board & National Academies of Sciences, Engineering, and Medicine, 2009).

3. Pavement friction and surface texture

Pavement friction is the force that resists the relative motion between a vehicle tire and a pavement surface. This resistive force, illustrated in Figure 3-1, is generated as the tire rolls or slides over the pavement surface.

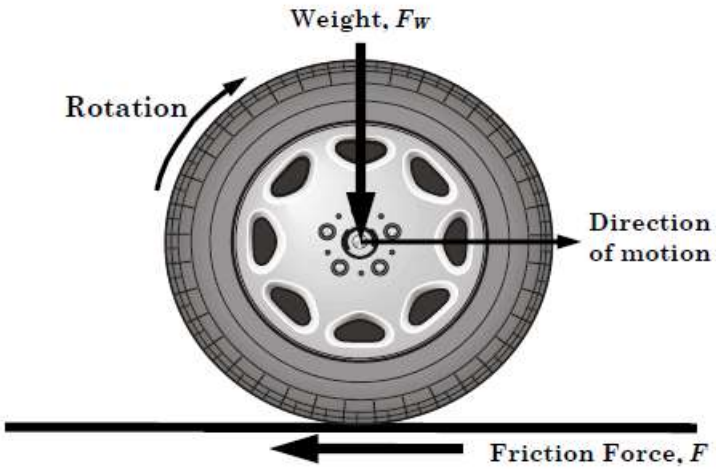


Figure 3-1 Simplified diagram of forces acting on a rotating wheel

The resistive force, characterized using the non-dimensional friction coefficient, μ, is the ratio of the tangential friction force (F) between the tire tread rubber and the horizontal traveled surface to the perpendicular force or vertical load (F_w), calculated as follows:

$$\mu = \frac{F}{F_w} \tag{1}$$

Pavement friction plays a vital role in keeping vehicles on the road, as it gives drivers the ability to control/maneuver their vehicles in a safe manner, in both the longitudinal and lateral directions. It is a key input for highway geometric design, as it is used in determining the adequacy of the minimum stopping sight distance, minimum horizontal radius, minimum radius of crest vertical curves, and maximum super-elevation in horizontal curves. Generally speaking, the higher the friction available at the pavement–tire interface, the more control the driver has over the vehicle.

3.1 LONGITUDINAL FRICTION FORCES

Longitudinal friction force is the force that acts along the direction of motion (or intended motion) of a wheel or tire due to friction with the surface. It occurs between a rolling pneumatic tire (in the longitudinal direction) and the road surface when operating in the free rolling or constant-braked mode. It is generated by tire-surface interactions:

- it arises when there is relative motion or a tendency for relative motion between the tire and the road.
- and depends on the coefficient of friction between the road and the tire.

This force plays a crucial role in vehicle dynamics:

- **vehicle acceleration**: the engine applies a torque to the wheels, generating a longitudinal force that propels the vehicle forward;
- the **braking system** reduces wheel speed, creating a friction force that opposes motion, slowing the vehicle.

- **Traction & Skidding:** if the applied force exceeds the available friction, the wheels may slip or skid.

Among influencing factors on this force we can find:

- **Road Conditions:** wet, icy, or rough surfaces affect the available friction.
- **Tire Characteristics:** tread pattern, inflation pressure, and tire material impact friction.
- **Load Distribution:** heavier loads increase normal force, enhancing friction.

Longitudinal friction force can be described by the following formula:

$$F_x = \mu_x \cdot N \tag{2}$$

where:

- μ_x = longitudinal friction coefficient
- N = normal force (perpendicular to the surface)

This force is also influenced by the **slip ratio**, which represents the difference between the actual wheel speed and the expected speed if rolling without slip:

- in the free-rolling mode (no braking), the relative speed between the tire circumference and the pavement—referred to as the slip speed—is zero.
- In the constant-braked mode, the slip speed increases from zero to a potential maximum of the speed of the vehicle.

The following relationship explains slip speed (Meyer, 1982)

$$\begin{aligned} S &= V - V_P \\ &= V - (0.68 \times \omega \times r) \end{aligned} \tag{3}$$

where:

- S = slip speed (kph)
- V = vehicle speed (kph)
- V_p= average peripheral speed of the tire (kph)
- ω = angular velocity of the tire (rad/s)
- r = average radius of the tire (m)

During free-rolling state of the tire, $V_p = V$, thus slip speed is 0.
For locked or fully braked wheel, $V_p = 0$, so the slip speed is equal to the vehicle speed V.
A locked-wheel state is often referred to as 100% slip ratio, while the free-rolling state is 0% slip ratio. The following relationship provides the calculation of the slip ratio SR (Meyer, 1982):

$$SR = \frac{V - V_P}{V} \times 100 = \frac{S}{V} \times 100 \tag{4}$$

Where:

- V = vehicle speed (kph)
- V_p= average peripheral speed of the tire (kph)
- S = slip speed (kph)

Figure 3-2 shows the ground force acting on a free rolling tire. In this mode, the ground force is at the center of pressure of the tire contact area and is off center by the amount a. This offset causes a moment that must be overcome to rotate the tire. The force required to counter this moment is called the rolling resistance force (F_R). The value a is a function of speed and increases with speed. Thus, F_R increases with speed.

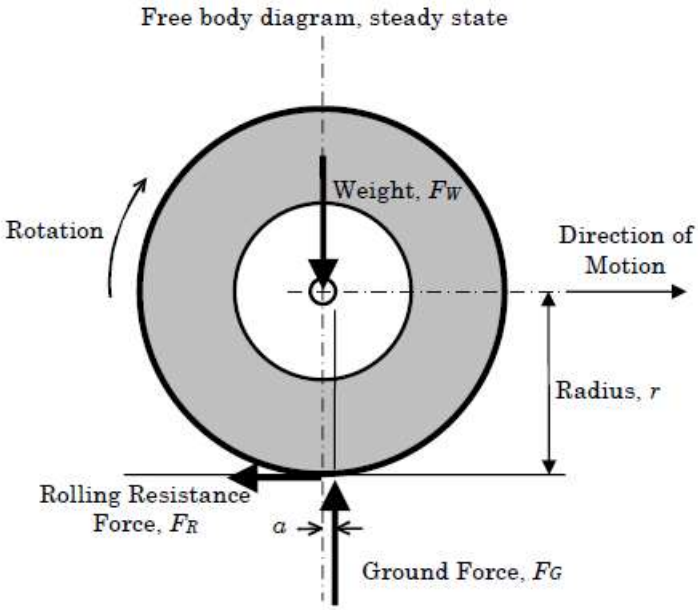


Figure 3-2 Rolling resistance force with free-rolling tire at constant speed on a bare dry paved surface

In the constant-braked mode (Figure 3-3), an additional force called the braking slip force (F_B) is required to counter the added moment (M_B) created by braking. The force is proportional to the level of braking and the resulting slip ratio.
The total frictional force is the sum of the free-rolling resistance force (F_R) and the braking slip force (F_B).

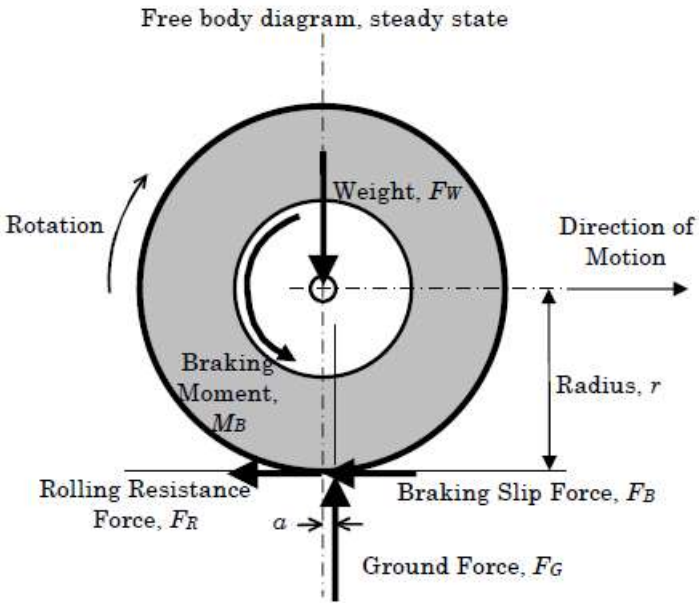


Figure 3-3 Forces and moments of a constant-braked wheel on a bare, dry paved surface

The coefficient of friction between a tire and the pavement changes with varying slip, as shown in Figure 3-4. The coefficient of friction increases rapidly with increasing slip to a peak value that usually occurs between 10 and 20% slip (critical slip). The friction then decreases to a value known as the coefficient of sliding friction, which occurs at 100% slip. The difference between the peak and sliding coefficients of friction may equal up to 50% of the sliding value, and is much greater on wet pavements than on dry pavements.

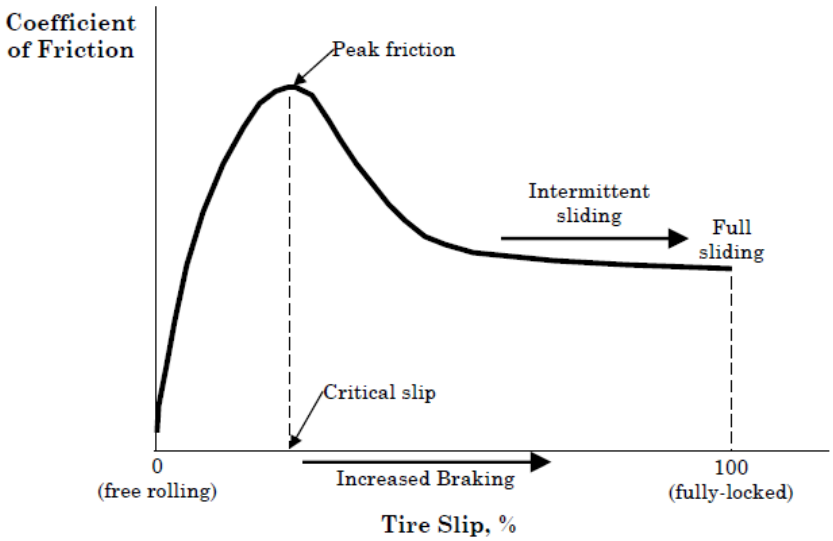


Figure 3-4 Pavement friction versus tire slip

The relationship shown in Figure 3-4 is the basis for the anti-locking brake system (ABS), which takes advantage of the front side of peak friction and minimizes the loss of side/steering friction due to sliding action. Vehicles with ABS are designed to apply the brakes on and off (i.e., pump the brakes) repeatedly, such that the slip is held near the peak. The braking is turned off before the peak is reached and turned on at a set time or percent slip below the peak. The actual timing is a proprietary design of the manufacturer.

3.2 LATERAL FRICTION FORCES

Another important aspect of friction relates to the lateral or side-force friction that occurs as a vehicle changes direction or compensates for pavement cross-slope and/or cross wind effects. Lateral friction forces, also known as lateral tire forces or cornering forces, are the forces that act perpendicular to the direction of wheel motion. These forces enable a vehicle to turn, maintain stability, and resist lateral slipping.

Lateral forces arise due to the interaction between the tire and the road when the wheel is steered. Among the key factors influencing this force, we retrieve the slip angle , that is the angle between the direction the tire is pointing and the actual direction of travel.

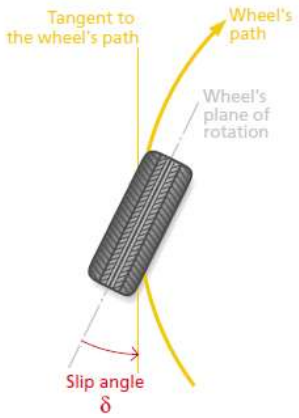


Figure 3-5 Simplified slip angle visualisation

When a vehicle turns, the tire does not follow a perfectly straight path; instead, it generates a lateral force to counteract the turning motion. This force is described as follows:

$$F_y = C_\alpha \cdot \alpha \tag{5}$$

Where:

- F_y = lateral force
- C_α = cornering stiffness
- α = slip angle
    - At small slip angles, the relationship is linear (tire response predictably)
    - At high slip angles, the tire enters non-linear regions (risk of sliding or losing grip)

The relationship between the forces acting on the vehicle tire and the pavement surface as the vehicle steers around a curve, changes lanes, or compensates for lateral forces is as follows

$$F_S = \frac{V^2}{15\,R} - e \tag{6}$$

Where:

- F_S = side friction
- V = vehicle speed (kph)
- R = radius of the path of the vehicle's center of gravity (also, the radius of curvature in a curve) (m)
- e = Pavement super-elevation (m/m)

This equation is based on the pavement–tire steering/cornering force diagram in Figure 3-5. It shows how the side-force friction factor acts as a counterbalance to the centripetal force developed as a vehicle performs a lateral movement.

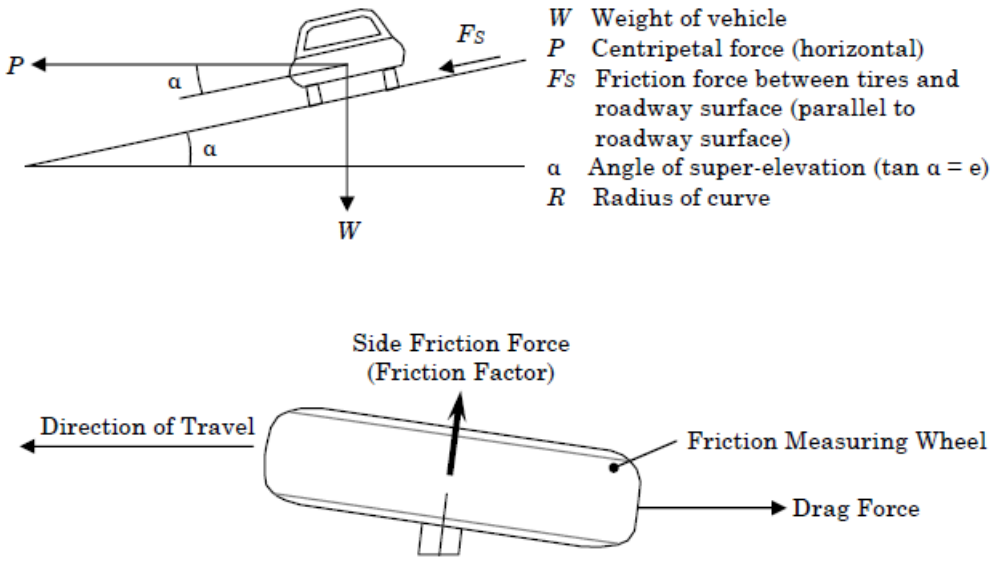
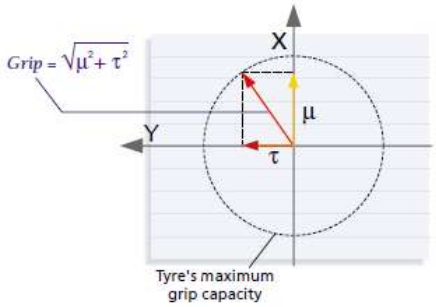


Figure 3-6 Dynamics of a vehicle traveling around a constant radius curve at a constant speed, and the forces acting on the rotating wheel.

3.3 COMBINATION OF BRAKING AND CORNERING

When a vehicle brakes while cornering, both longitudinal (braking) forces and lateral (cornering) forces act on the tires simultaneously. The available friction must be shared between these two forces, which affects the vehicle's stability and handling.
The friction circle (or ellipse) describes the maximum force a tire can generate in both longitudinal and lateral directions:

$$\left(\frac{F_x}{\mu N}\right)^2 + \left(\frac{F_y}{\mu N}\right)^2 \leq 1 \qquad (7)$$



X: Longitudinal friction force
Y: Transversal friction force

Where:

- F_x = Longitudinal force (braking or acceleration)
- F_y = Lateral force (cornering)
- μN = Maximum available friction force

The friction potential is shared between longitudinal and lateral. If a tire is using all its friction for braking, it has no grip left for cornering. Conversely, if it's fully cornering, additional braking can cause a skid. With combined braking and cornering, a driver either risks not stopping as rapidly or losing control due to reduced lateral/side forces. When operating at the limits of tire grip, the interaction of the longitudinal and lateral forces is such that as one force increases, the other must decrease by a proportional amount. The application of longitudinal braking reduces the lateral force significantly. Similarly, the application of high lateral force reduces the longitudinal braking.

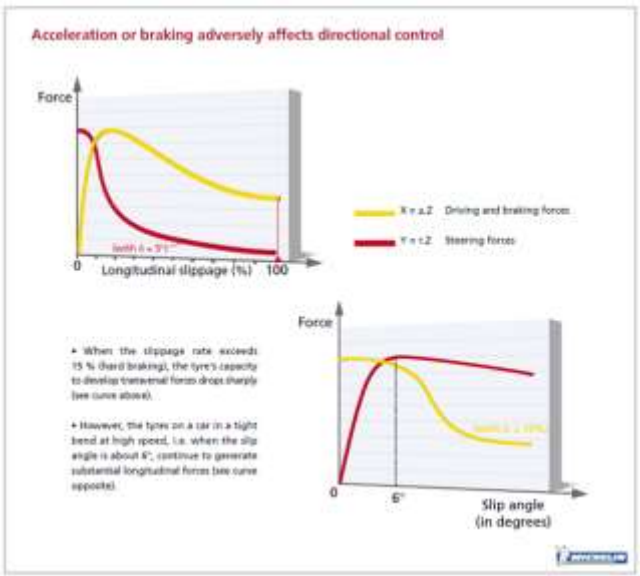


Figure 3-7 Illustration of friction shared between longitudinal and lateral forces

3.4 FRICTION MECHANISMS

Pavement friction is the result of a complex interplay between two principal frictional force components - adhesion and hysteresis.

Adhesion is the friction that results from the small-scale bonding/interlocking of the vehicle tire rubber and the pavement surface as they come into contact with each other. It is a function of the interface shear strength and contact area.

The **indentation** component of frictional forces results from the energy loss due to bulk deformation of the vehicle tire on the road roughness. The deformation is commonly referred to as enveloping of the tire around the texture. When a tire compresses against the pavement surface, the stress distribution causes the deformation energy to be stored within the rubber. As the tire relaxes, part of the stored energy is recovered, while the other part is lost in the form of heat (hysteresis), which is irreversible. That loss leaves a net frictional force to help stop the forward motion.

$$F = F_A + F_H \tag{8}$$

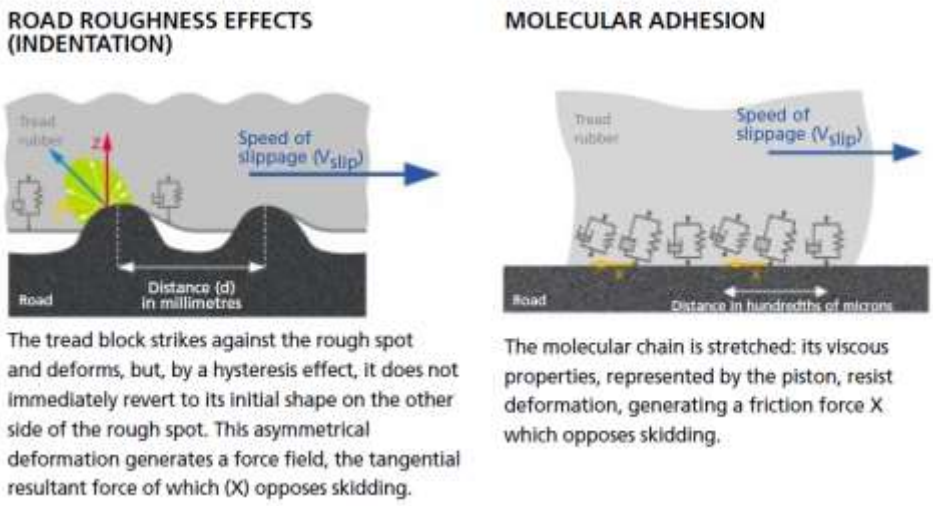


Figure 3-3-8 Illustration of the friction mechanisms

Both components depend largely on pavement surface characteristics, the contact between tire and pavement, and the properties of the tire. Also, because tire rubber is a visco-elastic material, temperature and sliding speed affect both components.

Because adhesion force is developed at the pavement–tire interface, it is most responsive to the micro-level asperities (micro-texture) of the aggregate particles contained in the pavement surface. In contrast, the hysteresis force developed within the tire is most responsive to the macro-level asperities (macro-texture) formed in the surface via mix design and/or construction techniques. As a result of this phenomenon, adhesion governs the overall friction on smooth-textured and dry pavements, while indentation is the dominant component on wet and rough-textured pavements.

3.5 FACTORS AFFECTING AVAILABLE PAVEMENT FRICTION

The factors that influence pavement friction forces can be grouped into four categories:

- pavement surface characteristics
- vehicle operational parameters
- tire properties
- environmental factors

Because each factor in this table plays a role in defining pavement friction, friction must be viewed as a process instead of an inherent property of the pavement. It is only when all these factors are fully specified that friction takes on a definite value.

3.5.1 SURFACE AND PAVEMENT TEXTURE

Pavement surface texture is characterized by the asperities present in a pavement surface. Such asperities may range from the micro-level roughness contained in individual aggregate particles to a span of unevenness stretching several feet in length. The two levels of texture that predominantly affect friction are micro-texture and macro-texture.
Micro-texture is the degree of roughness imparted by individual aggregate particles, whereas macro-texture is the degree of roughness imparted by the deviations among particles

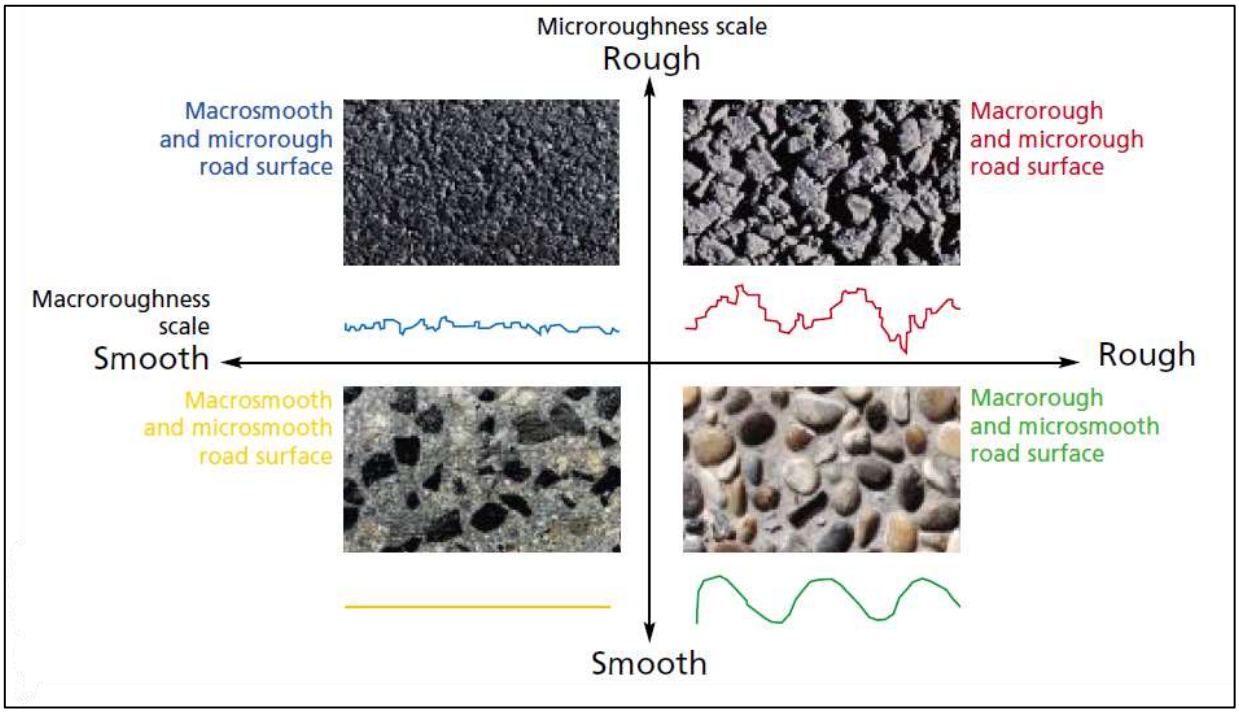
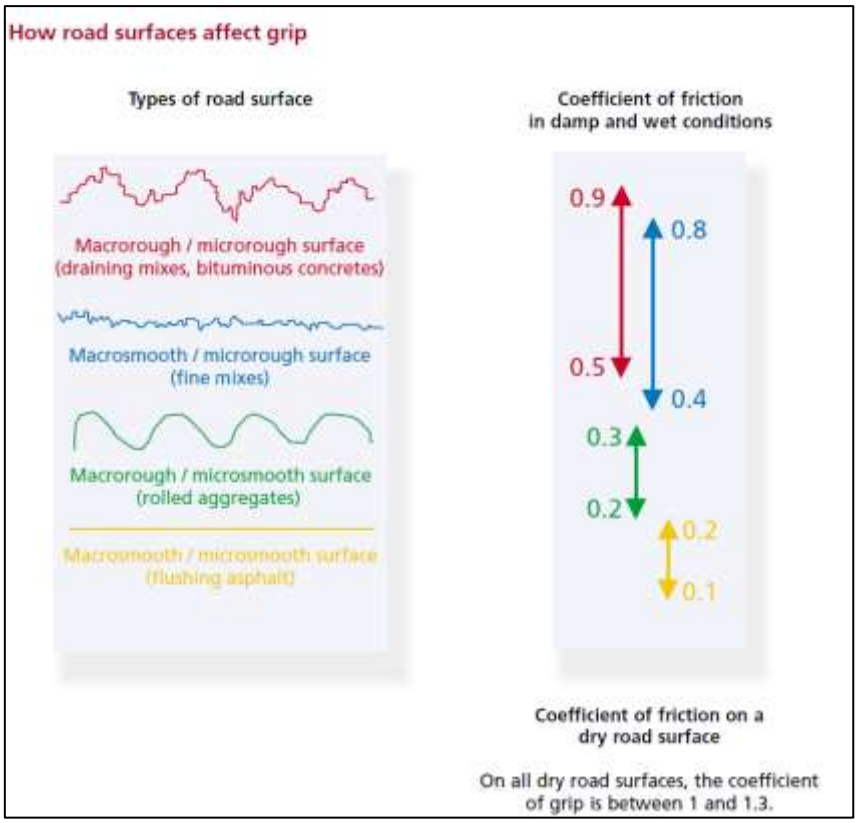


Figure 3-3-9 Illustration of the road roughness scales

Pavement surface material properties (i.e., aggregate and mix characteristics, texturing patterns) help to define surface texture. These properties also affect the long-term durability of texture through their capacities to resist aggregate polishing and abrasion/wear of both aggregate and mix under accumulated traffic and environmental loadings.



3.5.2 Vehicle Operating Parameters

The coefficient of friction between a tire and the pavement changes with varying slip. It increases rapidly with increasing slip to a peak value that usually occurs between 5 and 15% slip. The friction then decreases to a value known as the coefficient of sliding friction, which occurs at 100% slip.

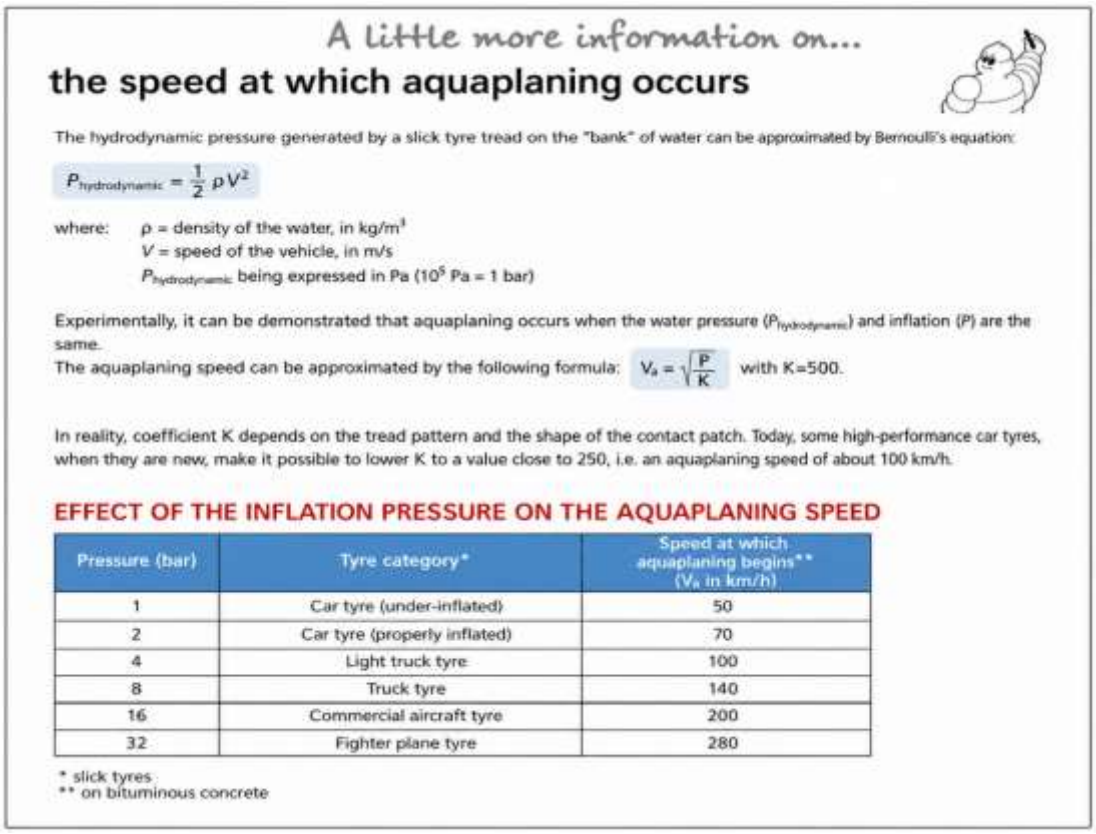
3.5.3 Tire Properties

3.5.3.1 Tire Tread Design and Condition

Tire tread design (i.e., type, pattern, and depth) and condition have a significant influence on the effective contact patch pressure and on draining water that accumulates at the pavement surface. Water trapped between the pavement and the tire can be expelled through the channels provided by the pavement surface texture and by the tire tread. The depth of tread is particularly important for vehicles driving over thick films of water at high speeds

3.5.3.2 Tire Inflation Pressure

Tire under-inflation can significantly reduce friction on wet conditions at high speeds. The main contribution is the link between the pressure in the contact patch (very closed to the inflation pressure) and the hydrodynamic pressure, as shown in Figure 3-10.



A little more information on...

the speed at which aquaplaning occurs

The hydrodynamic pressure generated by a slick tyre tread on the "bank" of water can be approximated by Bernoulli's equation:

$$P_{hydrodynamic} = \frac{1}{2}\rho V^2$$

where: ρ = density of the water, in kg/m³
V = speed of the vehicle, in m/s
$P_{hydrodynamic}$ being expressed in Pa (10^5 Pa = 1 bar)

Experimentally, it can be demonstrated that aquaplaning occurs when the water pressure ($P_{hydrodynamic}$) and inflation (P) are the same.
The aquaplaning speed can be approximated by the following formula: $V_a = \sqrt{\frac{P}{K}}$ with K=500.

In reality, coefficient K depends on the tread pattern and the shape of the contact patch. Today, some high-performance car tyres, when they are new, make it possible to lower K to a value close to 250, i.e. an aquaplaning speed of about 100 km/h.

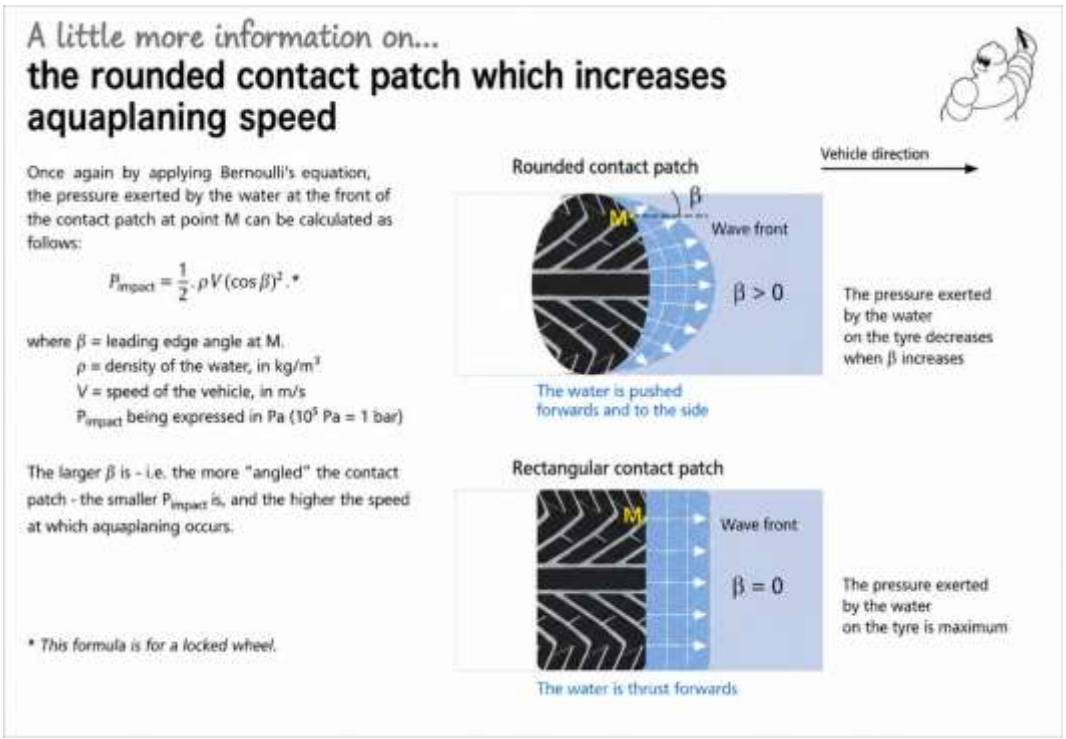
EFFECT OF THE INFLATION PRESSURE ON THE AQUAPLANING SPEED

Pressure (bar)	Tyre category*	Speed at which aquaplaning begins** (V_a in km/h)
1	Car tyre (under-inflated)	50
2	Car tyre (properly inflated)	70
4	Light truck tyre	100
8	Truck tyre	140
16	Commercial aircraft tyre	200
32	Fighter plane tyre	280

* slick tyres
** on bituminous concrete

Figure 3-10: Speed of aquaplaning

The other secondary contribution is the link between the pressure and the shape of the contact patch (an increased pressure will generate a more rounded contact patch), as shown in Figure 3-11.



A little more information on...

the rounded contact patch which increases aquaplaning speed

Once again by applying Bernoulli's equation, the pressure exerted by the water at the front of the contact patch at point M can be calculated as follows:

$$P_{impact} = \frac{1}{2}.\rho V(\cos\beta)^2.*$$

where β = leading edge angle at M.
ρ = density of the water, in kg/m³
V = speed of the vehicle, in m/s
P_{impact} being expressed in Pa (10^5 Pa = 1 bar)

The larger β is - i.e. the more "angled" the contact patch - the smaller P_{impact} is, and the higher the speed at which aquaplaning occurs.

* *This formula is for a locked wheel.*

Rounded contact patch

Vehicle direction

M

β

Wave front

β > 0

The pressure exerted by the water on the tyre decreases when β increases

The water is pushed forwards and to the side

Rectangular contact patch

M

Wave front

β = 0

The pressure exerted by the water on the tyre is maximum

The water is thrust forwards

Figure 3-11: Link between contact patch and aquaplaning

3.5.4 ENVIRONMENT

3.5.4.1 Thermal Properties

Automotive tires are visco-elastic materials, and their properties are significantly affected by changes in temperature. On standard passenger cars, pavement–tire friction generally decreases at hot tire temperature.

3.5.4.2 Water

Water, in the form of rainfall or condensation, can act as a lubricant, significantly reducing the friction between tire and pavement.

The presence of water interferes with grip mechanisms.

Molecular adhesion can no longer operate if contact between the rubber and road surface is not perfectly clean and dry. That effect occurs at all speeds.

Indentation is inoperative if the depth of water covers the tiny bumps in the road surface. In wet weather, maintaining grip therefore involves dispersing the water to restore dry contact between the tread and the road. That effect is amplificated by the depth of water and the speed of the vehicle, but also by wear of the tire.

Maximum grip (μ_{max}) depending on depth of water and speed.
Examples on a macrorough and microrough road surface

Depth of water	Speed 60 km/h	100 km/h
0 (dry surface)	1	1
< 10 µm (damp surface)	0.8	0.7
1.5 mm	0.6	0.4
5 mm	0.5	0.1



3.5.4.3 Snow and Ice

Snow and ice on the pavement surface present the most hazardous condition for vehicle braking or cornering, and required a specific tire fittement. With standard summer tires, the level of friction between the tires and the pavement is such that almost any abrupt braking or sudden change of direction can results in locked-wheel sliding and loss of vehicle directional stability.

3.5.4.4 Contaminants

Contaminants commonly found on highways include dirt, sand, oil, water, snow, and ice. Any kind of contamination at the pavement–tire interface will have an adverse effect on pavement–tire friction. Foreign materials act like the balls in a ball bearing, or as lubricant

between a piston and cylinder in an engine, reducing friction between the two surfaces. The thicker or more viscous the contaminant, the greater the reduction in pavement–tire friction. The grinding effect of hard contaminants, such as sand, accelerates the rate of wearing at the pavement surface.

3.6 IMPACT OF FRICTION ESTIMATION IN AUTOMOTIVE CONTROL

Accurate friction estimation plays a critical role in vehicle safety, performance, and efficiency. Here's how it impacts different aspects of automotive control:

- **Stopping Distance**
  - Friction directly influences braking performance. Higher friction shortens stopping distances, while lower friction (e.g., wet, icy roads) increases stopping distances.
  - Anti-lock Braking Systems (ABS) rely on real-time friction estimation to optimize braking force and prevent wheel lockup.
  - Emergency braking systems (AEB) don't systematically rely on dynamic friction estimates to calculate the stopping distance. They use predictive models based on standard scenarios and environmental sensors. The integration of real grip remains an axis of research and improvement.
- **Deceleration Rate Measurement**
  - The rate at which a vehicle slows down depends on tire-road friction.
- **Electronic Stability Control** (ESC) adjusts braking and engine torque based on friction levels to manage skidding up to its limits.
- **Traction Control Systems** (TCS) modulate wheel slip based on estimated friction, ensuring stability during acceleration.
- **Autonomous and Advanced Driver-Assistance Systems** (ADAS)
  - Self-driving cars need precise friction estimation for safe navigation, adaptive cruise control, and lane-keeping assistance.
- **Path planning algorithms** adjust speed and trajectory based on road conditions.
- **Energy Efficiency and Tire Wear**
  - Optimizing acceleration and braking based on friction levels can improve fuel efficiency and reduce tire wear.
  - Regenerative braking systems in EVs adjust energy recovery based on road friction.

Friction estimation enhances vehicle safety, control, and efficiency by enabling adaptive braking, stability control, and autonomous decision-making. Accurate real-time friction estimation is crucial for both human-driven and self-driving vehicles.

3.7 MEAN TO MONITOR THE ADHERENCE

Monitoring adherence (tire-road friction) is crucial for vehicle safety and control. Several methods are used to estimate and monitor friction in real-time:

1) **Sensor-Based Approaches**
   - **a.** Wheel Speed Sensors: Detect slip ratio and provide input for ABS and TCS.
   - **b.** Accelerometers & Gyroscopes: Measure vehicle dynamics and detect traction loss.
   - **c.** Force and Torque Sensors: Measure the forces acting on tires for real-time friction estimation.
   - **d.** Other sensors can also be used for grip monitoring (TMS, microphones, …)
2) **Vision and Radar-Based Systems**
   - **a.** Cameras & LiDAR: Analyze road texture and surface conditions (e.g., dry, wet, icy).
   - **b.** Radar Sensors: Estimate road roughness and detect water or ice on the pavement.
3) **Machine Learning & AI-Based Estimation**
   - **a.** Predictive Models: Use historical and real-time data to estimate friction.
   - **b.** Neural Networks: Learn from different road conditions and adapt vehicle responses accordingly.
4) **Vehicle Behavior Analysis**
   - **a.** Braking and Steering Response: Monitors how the vehicle reacts to driver inputs.
   - **b.** Slip and Skid Detection: Identifies loss of traction and adjusts braking/acceleration accordingly.
5) **Connected Vehicle Systems**
   - **a. V2X Communication**: Vehicles share road friction data with other vehicles and infrastructure.
   - **b. Cloud-Based Data Processing**: Uses crowd-sourced data to predict friction conditions ahead.

Some of these solutions can measure with precision the current grip under the tires, even at low dynamics), but they won't predict the oncoming grip with is the more important to take the good decision.
Other solutions can predict the oncoming grip but with less precision. the more advanced solutions need to combine this to kind of technologies, to predict the oncoming grip and correct the prediction with the real-time measured grip.
Monitoring adherence using a combination of sensors, AI, and connected systems enhances safety, stability, and driving performance. These technologies are essential for autonomous vehicles and advanced driver-assistance systems (ADAS).

4. Conclusion

The safety of vehicles in wet conditions is critically influenced by the friction between tires and the road surface. This report demonstrates that reduced pavement friction, often caused by water, snow, ice, or surface wear, significantly increases the risk and severity of road accidents. Numerous studies have confirmed a direct correlation between low friction values and higher crash rates, particularly during adverse weather.

Understanding and improving tire-road friction is therefore a key factor in enhancing road safety. This includes both infrastructure-side measures—such as optimizing pavement texture, ensuring proper drainage, and maintaining adequate surface conditions—and vehicle-side technologies, including ABS, ESC, TCS, and ADAS systems that rely on accurate real-time friction estimation.

Moreover, advancements in sensor technologies, AI-based estimation models, and connected vehicle systems enable better monitoring and adaptation to varying road conditions. These tools support safer driving, better vehicle control, and informed decision-making in both human-driven and autonomous vehicles.

Ultimately, increasing the availability and precision of friction estimation systems, alongside targeted infrastructure improvements, will help reduce accident rates and improve the overall safety and efficiency of road transportation in adverse weather conditions.

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7. Table of illustrations

Figure 2-1Relationship between wet-weather crash rates and pavement friction for Kentucky highways (Rizenbergs, 1972) 7
Figure 2-2 Ratio of wet-to-dry pavement crashes versus pavement friction for Kentucky highways (Rizenbergs, 1972) 7
Figure 3-1 Simplified diagram of forces acting on a rotating wheel 9
Figure 3-2 Rolling resistance force with free-rolling tire at constant speed on a bare dry paved surface 11
Figure 3-3 Forces and moments of a constant-braked wheel on a bare, dry paved surface 11
Figure 3-4 Pavement friction versus tire slip 12
Figure 3-5 Simplified slip angle visualisation 12
Figure 3-6 Dynamics of a vehicle traveling around a constant radius curve at a constant speed, and the forces acting on the rotating wheel 13
Figure 3-7 Illustration of friction shared between longitudinal and lateral forces 14
Figure 3-3-8 Illustration of the friction mechanisms 15
Figure 3-3-9 Illustration of the road roughness scales 16
Figure 3-10: Speed of aquaplaning 18
Figure 3-11: Link between contact patch and aquaplaning 18