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Review

Progress and Monitoring Opportunities of Skid Resistance in Road Transport: A Critical Review and Road Sensors

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Abstract: Skid resistance is a significant feature that provides consistent traffic safety management for road pavements. An appropriate level of Skid resistance describes the contribution that the pavement surface makes to tire/road friction, and the surface of the road pavement can reduce vehicle operation cost, traffic accidents, and fatalities, particularly in wet conditions. Wet conditions decrease the level of the skid resistance (pavement friction), and this may lead to serious struggles related to driving on the road pavement (e.g., skidding or hydroplaning), which contributes to higher crash rates. The knowledge of skid resistance is essential to ensure reliable traffic management in transportation systems. Thus, a suitable methodology of skid resistance measurement and the understanding of the characterization of the road pavement are key to allow safe driving conditions. This paper presents a critical review on the current state of the art of the research conducted on skid resistance measurement techniques, taking into account field-based and laboratory-based methodologies, and novel road sensors with regard to various practices of skid resistance, factors influencing the skid resistance, the concept of the minimum skid resistance and thresholds. In conclusion, new trends that are relevant to data collection approaches and innovative procedures to further describe the data treatment are discussed to achieve better understanding, more accurate data interoperability, and proper measurement of skid resistance.

Keywords: skid resistance; infrastructure assessment; road friction; data analysis; interoperability; NDT; road sensors

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1. Introduction of Skid Resistance

1.1. Background

Safe roads are essential to ensure the reliable movement of goods and people within the transport system. Multiple factors influence road collisions, which are usually grouped into three different categories, namely features related to drivers (e.g., stopping distance, driver skills and behavior of drivers, and vehicle speed), features related to the vehicle (e.g., tire and loading characteristics, vehicle design, and brake performance) and aspects corresponding to the roadway conditions (e.g., roadway geometry, traffic control measurement systems, and pavement conditions) [1]. Nevertheless, a remarkable relationship between accident rates and such aspects of pavement surfaces as friction and pavement texture has been investigated in previous studies [2–4]. The number of crashes was linked to the friction values of the road surface; a higher friction value was concluded, primarily based on empirical data, to decrease the number of accidents, particularly in dry conditions, [5]. Poor surfaces of pavements with low skid resistance, inadequate visibility due to the spray used in wet conditions, and insufficient friction between vehicle tires and the

surface of the pavement may lead to uncontrolled skidding and cause severe traffic crashes within the transportation system [6]. Moreover, over 1.35 million people die and between 20 and 50 million are injured each year from different causes of road traffic crashes around the world according to the World Health Organization (WHO) and the authors of [7–9]. On the other hand, in Europe, around 23,400 persons die each year in road accidents: 45% of the fatalities are passenger car drivers or passengers, and 21% are pedestrians, according to the statistics provided in [2]. Traffic management studies indicate that 20% of traffic crashes are due to wet-weather conditions, which decrease the frictional resistance of the pavement surface [10,11]. The frictional resistance of the pavement surface is considered to be fundamental feature of the driving task, which ensures the safe maneuvering of vehicles in both the longitudinal and transversal directions [12]. Another definition of skid resistance is the force generated when a tire is prevented from sliding in a circular manner on the pavement surface [13,14]. It is a crucial parameter among the characteristics of the pavement surface, and significantly influences the efficiency of the roadway traffic system. Pavement assessment is essential to provide valuable information related to friction value, and can be considered as a supporting tool to deliver appropriate maintenance and repair procedures to ensure a safe roadway system in all weather conditions. Consequently, comprehensive knowledge of skid resistance prediction and pavement surface characteristics can lead, as a function of different roadway parameters, to a reliable traffic management system.

1.2. Objectives

Road transport infrastructure assessment is essential. Several studies have been conducted to provide an adequate assessment of road transportation [15–19]. Previous works focused on providing a general review of skid resistance and specific models of the road surface pavements, or covered laboratory experiments or on-site inspection for a specific methodology of skid resistance measurement. The objective of this work is related to skid resistance measurement via the consideration of the current progress in the field and the monitoring of opportunities offered by new techniques, for example, the road-based sensor approach and image-based techniques. A critical review of the published research on the skid resistance of pavements is presented, including current challenges, methodologies, and factors that influence skid resistance. New research trends concerning the exploitation of destructive and non-destructive testing, and road-based sensors used to evaluate the frictional resistance between tires and the pavement surface, are presented. Future trends and the use of new emerging technologies such as the application of machine learning and intelligent data analysis approaches are illustrated in order to achieve accurate interoperability of the collected research within the field. Several points are highlighted as contributions of this review paper, and are organized into four main themes:

- The state of the art in terms of skid resistance, particularly the concept of minimum thresholds, is elaborated.
- Factors influencing skid resistance are classified, and environmental conditions are also explored.
- New skid resistance measurement techniques are illustrated, with consideration of new challenges and methodologies related to contactless and semi-contactless techniques.
- Current methodologies, European research projects, and new advances in data analysis and interoperability are discussed.

1.3. Review Methodology

The authors aim to establish a critical understanding of skid resistance through several sections. The classification and methodologies used, and the grouping of papers into different topics, are outlined in the current section (see Figure 1).

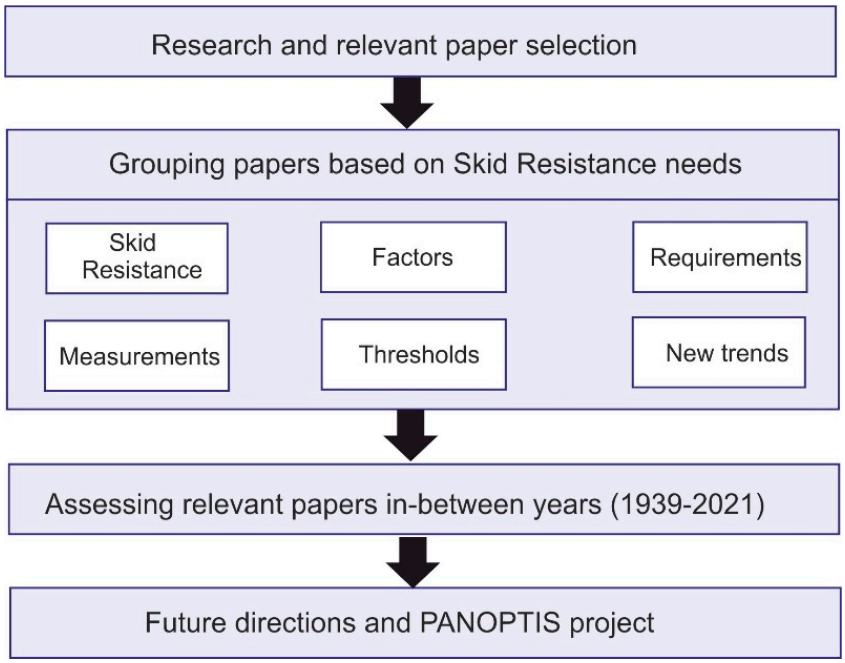


Figure 1. Review methodology framework.

The following factors are considered in this review in order to systematically understand the research within its scope (see Figure 1):

- Numerous studies are considered in relation to skid resistance methodologies (see reference list).
- This review research paper covers more than 80 years, between 1939 and 2021, and considers more than 80 papers (see Figure 2), in which updates to skid resistance test methods are elaborated upon.
- Key words are used to search for papers (skid resistance methodologies, skid resistance models, new trends in skid resistance, current challenges in skid resistance, factors affecting skid resistance, and road-based sensors) in different databases such as Scopus, Science direct and Web of Science in order to select relevant papers.
- Selected papers are based on different criteria (see Figure 1).
- Factors affecting skid resistance, the concept of skid resistance thresholds, and skid resistance requirements are listed.
- New European research project results are included, which are related to infrastructure assessment and, in particular, to the challenges related to skid resistance on surface pavements.
- New trends and future directions are also given.

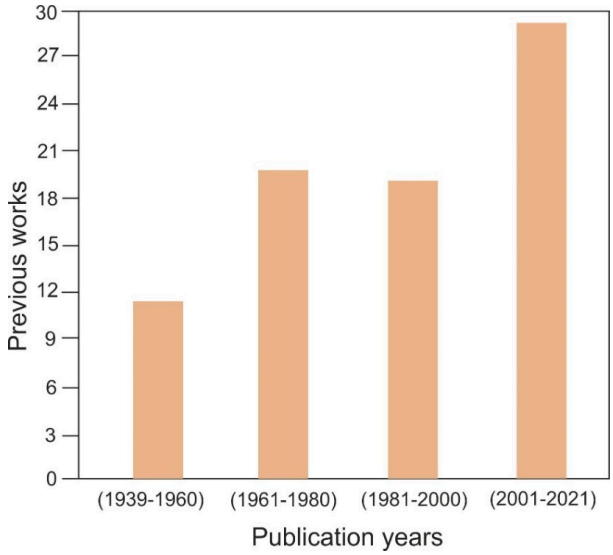


Figure 2. Number of previous research works included in this study versus publication years.

2. Factors Influencing Skid Resistance

Pavement friction is commonly defined as the force that resists the relative movements between a vehicle tire and the surface of the road pavement. Thus, skid resistance is generated due to the rolling or sliding of vehicle tires on the pavement surface [5,20]. Various factors can, directly and indirectly, influence the changes occurring in the skid resistance of the surface pavement. Table 1 shows a critical summary list of the main factors that affect the skid resistance of surface pavements.

Table 1. Factors affecting the pavement surface skid resistance (modified from [12,20]), grouped into 6 categories.

Road Surface Characteristics	Traffic Conditions	Vehicle Operations	Road Users	Tire Properties	Environmental Conditions
1. **Microtexture**	1. **Traffic load**	1. **Slip speed** (SP) as a function of:	1. **Lack of knowledge about skid resistance reduction**	**Tread design and conditions**	1. **Temperature** (°C)
2. **Macrotexture**	**2. Traffic density**	1.a. Vehicle speed, V	2. Inattention	**Inflation pressure**	2. **Water content;**
3. **Material characteristics**	3. Congestion	1.b. Slip ratio % (G)	3. Applied conditions of road pavement due to extreme weather conditions	Rubber configuration and rigidity	2.a. Rainfall
4. Megatexture		1.c. Braking System	4. **Stopping distance**	Foot print	2.b. Condensation
5. Roughness/ unevenness		1.d. Vehicle age	5. **Driving manoeuvre**	Tire load	3. **Snow and ice/freezing conditions**
6. Geometric of pavements		1.e. Capacity of engine	5.a. Turning	**Tire temperature**	4. **Contamination**
6.a. Curves		1.f. Suspension stability	5.b. Overtaking		4.a. Sand/dust
6.b. Slopes		1.g. Vehicle load			4.b. Salt
7. Temperature (°C)		1.h. Electronic stability control			4.c. Dirt
					d. Mud
					4.e. Organic materials
					4.f. Organic debris
					4.g. Rubber particles
					4.h. Wind

Note that critical factors in each category are presented in bold.

A summary of classified factors affecting skid resistance is presented in Table 1; these factors are classified into six categories that are related to the road pavement and vehicle operation, including traffic conditions, driver behavior, environment, and tire properties. Each is described in the following sections.

2.1. Category A: Pavement Surface Characteristics

Skid resistance is a crucial parameter of the surface pavement, which can offer an efficient means of better understanding the road surface for traffic operation purposes. It is a measurement of friction obtained under specified, standardized conditions, and is intended to fix the values of potential variable factors so that the contribution that the pavement provides to tire/road friction can be isolated [21]. A non-dimensional friction coefficient can be calculated based on the pavement surface forces acting on the rotating wheels. The pavement surface friction coefficient requires the transmission of all of the forces related to a given maneuver under a given set of conditions, and is obtained as follows (see Figures 3 and 4 for details of adhesion and hysteresis forces [5,20], and mathematical expression 1 below):

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

where μ is the non-dimensional friction coefficient, F is the tangential friction force between the tire tread rubber and the horizontal travelled surface and F_w is the perpendicular force or vertical load.

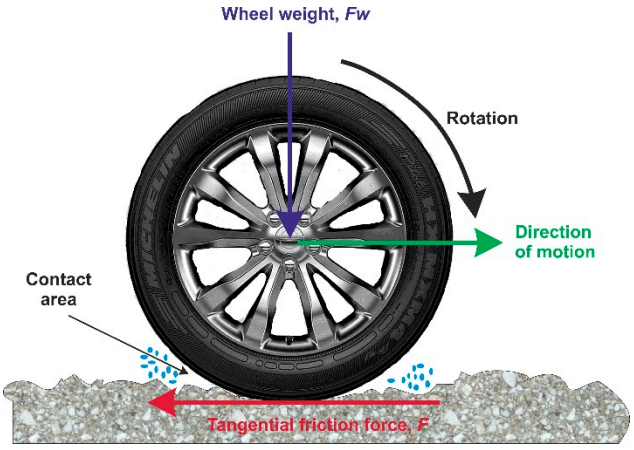


Figure 3. Typical sketch of forces acting on a rotating wheel (concept taken from [5,20]).

Theoretically, a complex interaction between tires and road pavements consists of two phenomena, such as molecular adhesion and hysteresis losses, and thus, the overall friction between the tire and the road surface is the sum of these two components [22,23]. Molecular adhesion is generated as a consequence of the shearing of molecular bonds (S) formed when the tire rubber is hard-pressed into a close contact area (A_i) with pavement surface particles (see Figure 4). Hysteresis losses are produced due to the energy dissipation of the deformed tire rubber when passing across the asperities of a rough pavement surface. The hysteresis losses relate to the energy that is stored (E_c) and dissipated (E_e) during tire–surface interaction for an acknowledged velocity (V) in that section. Thus, energy losses (C) happen during tire–surface interaction as the rubber is consecutively compressed and expanded. Generally, pavement surface adhesion friction decreases when the hysteresis losses increase [7,24,25]. These two components of skid resistance are related to the two key properties of road pavement surfaces: micro-texture and macro-texture (see Figure 4).

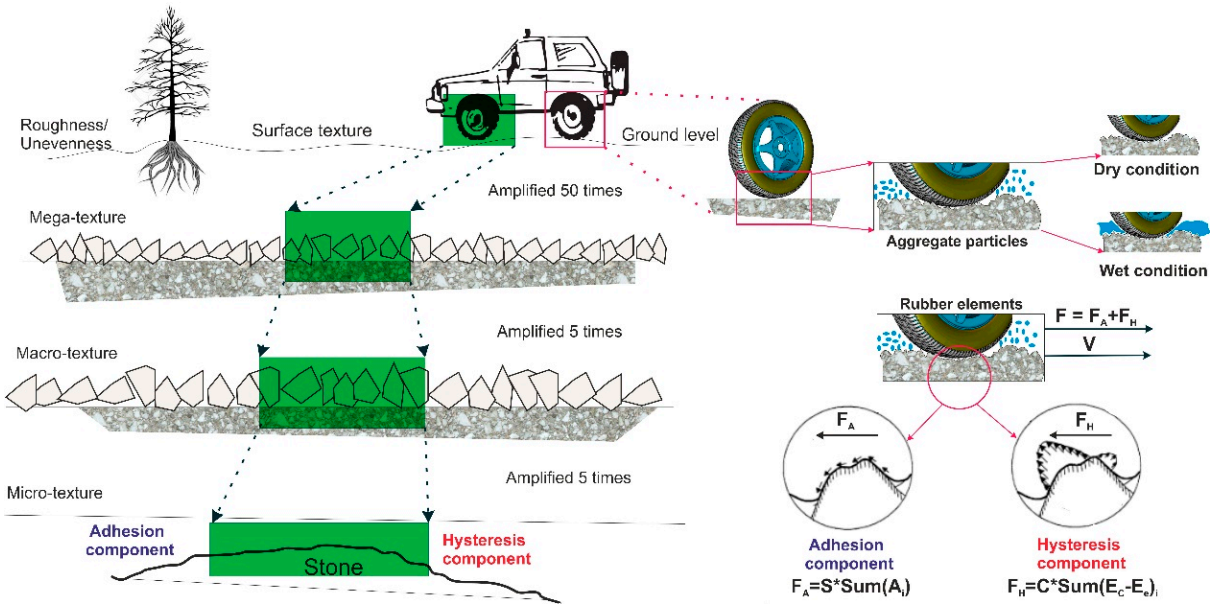
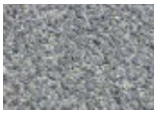


Figure 4. A typical schematic of the rubber-tire and pavement surface interaction components.

Friction phenomena are generated through the interaction of the tire and the road surface, even though there are several components in a roadway system that influence the friction mechanism. The pavement surface texture is a crucial characteristic, and it is based on the characterization of pavement asperities, specifically the grain roughness of the pavement mixture. The surface texture is a key parameter of the road surface, and it can include phenomena ranging from micro-level roughness to a span of unevenness stretching across the road surface [5,8,9,26]. Adequate use of the asphalt mix can increase friction, reduce water spraying and splashing, and abate noise. The scales of surface texture were defined in the XVII World Road Congress in Brussels in 1987 by the World Road Association (PIARC). Thus, the surface texture is divided into four categories as a function of the wavelength (λ) [25,26], and the amplitude (A) of the deviations (more details are given in Table 2), and each texture is explained separately. The two main levels of surface texture that predominantly affect the skid resistance are the micro-texture and the macro-texture [5,10]:

Table 2. Pavement texture classification according to the wavelength and amplitude (modified from [26]).

No.	Level of Texture	Wavelength, λ (mm)	Amplitude, A (mm)	Texture View
1	Micro-texture	$0 < \lambda < 0.5$	$0.001 < A < 0.5$	
2	Macro-texture	$0.5 < \lambda < 50$	$0.1 < A < 20$	
3	Mega-texture	$50 < \lambda < 500$	$1 < A < 50$	
4	Roughness or unevenness	$\lambda > 500$	$1 < A < 200$	

- Microtexture is a fine-scale texture characteristic that is based on the surface properties of the asphalt mix, which include its size and shape, as well as the gradient of the aggregate, and on the asphalt/bitumen materials used to generate molecular adhesion (see Figure 4). The microtexture depends on the roughness of the aggregate surface [27,28]. It is considered to be one of the main features that can affect the skid resistance on the pavement surface. The level of texture of the microtexture is assumed according to its wavelength ($0 < \lambda < 0.5$) (measured in mm) and its amplitude ($0.001 < A < 0.5$) [6].
- Macrotexture is a larger (coarse) scale texture characteristic, which is based on the existence of voids between aggregate particles and takes into account the larger size, shape, and gradient of the coarse aggregate in the asphalt mix. The macrotexture is the main characteristic that produces a loss of hysteresis (see Figure 4). Water can escape from channels at the macrotexture level of the surface pavement, thus decreasing hydroplaning. This texture level is assessed according to its wavelength ($0.5 < \lambda < 50$) (measured in mm) and its amplitude ($0.1 < A < 20$) [12,26].

Despite the significant influence of the microtexture and macrotexture on the generation of skid resistance, additional pavement surface textures are also very important pavement characteristics (i.e., megatexture and roughness (unevenness)), including the following:

- Megatexture is a texture that corresponds to the irregularities (e.g., distress, defects, or waviness) associated with rutting, potholes, patching, surface stone loss, and major joints and cracks in the road surface [27–29]. The megatexture influences the noise level and the rolling resistance more than the skid resistance of the road pavements. The texture level considered in this category is ($50 < \lambda < 500$) and ($1 < A < 50$) in terms of wavelength and amplitude, respectively [12,29].
- Roughness (unevenness) is a larger texture than the megatexture, and it can also influence the rolling resistance as well as the driving quality and the operation costs of the vehicles. Computing the overall measure of the surface pavement condition is usually based on the International Roughness Index (IRI). This texture level is ($\lambda > 500$) for wavelength and ($1 < A < 200$) for amplitude [27,28]

Pavement texture properties are an essential feature in terms of understanding the tire–road interaction while taking into account various parameters (e.g., wet conditions, the age of the pavement, binder, noise, tire wear, rolling resistance and splash or spray, and the geological properties of the aggregate). The aggregates represent approximately 90% (or more) of the bitumen mixture in weight, and 95% of the total mix of pavement materials. For this reason, the level of influence of the aggregate characteristics (e.g., shape, angularity, abrasion, and hardness) on skid resistance is high. The role of the aggregate macrostructure is to induce the hysteresis force of the tire and to release water drainage in between the tire and the road pavement surface area. Furthermore, it is used to provide a microtexture that facilitates and maintains safe friction levels on the road surface [24,25]. Geometric elements of the roadway, such as grade and curvatures, can also influence the skid resistance [30]. Several research studies have been conducted to understand the polishing of aggregates, which is principally defined as an abrasion of the small particles of aggregate asperities (microtexture) that results from rubbing action that occurs after grinding and shearing caused by repeated traffic loadings. The polishing of aggregates is one of the most significant pavement texture properties that affects the functionality of the road surface, and it also affects the standard level of the road surface's skid resistance. This can be measured by means of Polish Stone Value (PSV) to provide information on the resistance to the polishing action of the vehicle tires; this information is related to the conditions of the road surface [8,9,25,27].

2.2. Category B: Traffic Conditions

Traffic conditions are also considered to have the potential to slightly impact the skid resistance, particularly during various conditions of heavy traffic load and density, which can influence the behavior and comfort of road users during traffic congestion [12,31].

2.3. Category C: Vehicle Operation Conditions

Vehicle operation factors have a significant influence on skid resistance in traffic management systems. It is well-known that skid resistance decreases at higher vehicle speeds in wet pavement conditions. Generally, the relative contribution of the pavement surface (e.g., microtexture and macrotexture) changes due to the continuous variations in the vehicle speed. Water trapped between the tires and road pavement may escape, and the escape time is reduced due to an increase in the vehicle speed; for this reason, adequate skid resistance is mandatory to ensure a safe maneuver [12,13].

The slip speed is the relative speed based on the vehicle tire circumferences and the surface road pavement in the condition of free rolling or constant-braked mode. A locked-wheel state corresponds to a 100% slip ratio, while a free rolling state corresponds to a 0% slip ratio. The friction coefficient increases significantly, to a high value, in cases in which critical slippage reaches the range of 10% to 20%. The friction decreases to a value known as the sliding friction coefficient when the slippage reaches 100% [12–20] (see Table 2).

The braking system of the vehicle is an efficient factor in terms of mitigation when the skid resistance is decreased to an unfavorable value. In particular, new vehicles commonly use high-tech brake systems, namely Antilock brake systems (ABS). ABS can maintain the slip ratio at 15%, which increases the surface force of the road pavement to allow the vehicle to stop in a safe and reliable manner. Several other factors can influence the skid resistance of the surface pavement (e.g., the vehicle age, the capacity of the engine, the suspension stability, and the vehicle load are also important factors that can impact the stability of vehicles, particularly when moving along curves at high speeds).

2.4. Category D: Road Users Behaviour

Driver behavior is considered to be one of the key factors for traffic safety when skid resistance reaches a low level. Road user behavior could contribute to increasing accident rates due to a lack of knowledge about the reducing of skid resistance, inattention, vehicle conditions, overload, and the impact of weather changes on the conditions of road pavement surfaces [12,31].

Driver behavior during driving tasks is interrelated with other factors such as vehicle operation, road surface, and vehicle design. A basic knowledge of skid resistance is recommended for drivers (Table 3). Road user behavior changes during adverse weather conditions depending on experience and risk tolerance; some drivers may slow down when they come across wet weather conditions, but others may preserve or even increase vehicle speeds [14]. On the other hand, the stopping distance between vehicles is also correlated with the friction coefficient of the road pavement surface, and this is directly controlled by drivers based on the driving task conditions. The average stopping distance is considered to be 67 to 121 m for ribbed tires and 68 to 155 m for vehicles without ribbed tires [15].

Considering that the exact limitations of vehicle speed can used to determine the maximum design speed for traffic management, stopping distances, in various weather conditions (the most critical is in wet conditions), could be recommended through traffic management authorities as temporary or permanent recommendations to be considered by road users. These required actions will support advancements in road users' and operators' knowledge of the skid resistance of road pavements.

Table 3. Possible actions to be taken into consideration for various road pavement conditions.

No.	Pavement Condition	Skid Resistance	Vehicle Speed	Additional Causes or Extreme Conditions	Actions that Need to Be Taken by Road Users
1	**Dry**	High	Low	Normal dry condition	• Considered as normal situation
2	**Wet**	Low	High	Normal wet condition	• Decrease the vehicle speed • Increase the stopping distance
3		Low	High	Tire age, or damaged tires (both wet and dry conditions)	• Control the vehicle speed due to the high possibility of accidents • Decrease the vehicle speed
4		Low	High	Curves, steep hills, edges, and junctions (both wet and dry conditions)	• The maneuver should be performed cautiously due to the increasing of the slip speed • Decrease the vehicle speed • Increase the stopping distance
5		Low	High	Snow or Ice	• Perform driving tasks with caution and decrease the vehicle speed • Decrease the vehicle speed • Increase the stopping distance
7		Low	High	Contamination	• Considered as unfavorable situation; park if needed • Increase the stopping distance • Decrease the vehicle speed

2.5. Category E: Tire Properties

The properties of tires affect the variation of skid resistance in both dry and wet conditions. Several properties of tires have various effects on skid resistance measurements, such as tire temperature, tire design and conditions, tire footprints, rubber configurations and rigidity (hardness), inflation pressure, and seasonal effects on tire pressure [16–19]. Tire temperature is not a fixed value during normal operation, and it can vary with speed, seasonal climate change, and also tire material and rubber properties [20,21].

The braking friction decreases with low inflation pressure and increases with the increasing of the axle load. The braking friction coefficient is also increased with the increasing of the vehicle speed [20,22]. The combination of ambient and pavement temperatures causes weak braking friction and rolling resistance coefficients. Other possible features are illustrated in Table 3.

2.6. Category F: Environmental Conditions

This section presents the effect of various environmental conditions which can, directly and indirectly, influence the pavement surface due to seasonal changes in climate, and also presents their influence on the safety of driving tasks for road users. The focus is on the most widely considered environmental factors, as illustrated in previous studies (e.g., temperature, rainfall, snow and ice, contamination of the road pavement, and wind). Table 3 presents details of the environmental conditions that influence skid resistance [32–39].

2.6.1. Impact of Temperature

Changes in temperature due to seasonal changes in climate have been known to directly and indirectly affect the skid resistance of the pavement surface.

Skid resistance is commonly measured during summer to determine the lowest value for the design of the road pavements. On the other hand, skid resistance varies slightly during the same day due to temperature changes. Thus, one considers wet conditions

during the high-temperature period [40–43]. On the other hand, water temperature and surface pavement temperature are highly correlated, and can directly influence the operation of the roadway system, but not its friction [30–44]. Temperature can modify the characterization of the design of the pavement mix; this can influence the skid resistance safety policies for driving tasks in roadways. In addition, previous studies showed that air, pavement, and tire temperature also affect skid resistance [23,45]. Tire temperature is proportional to air temperature, and skid resistance decreases with higher temperature. High pavement temperature decreases the friction of the road pavement. To assess this, various formulae are proposed to model the relationship between the temperatures from air, tires, and pavements:

$$T_t = 8.45 + 0.810 * T_A \qquad \left(R^2 = 0.83\right) \tag{2}$$

$$T_t = 6.78 + 0.558 * T_P \qquad \left(R^2 = 0.76\right) \tag{3}$$

$$T_A = 0.87 + 0.573 * T_P \qquad \left(R^2 = 0.80\right) \tag{4}$$

where T_t = Tire temperature (°C), T_p = Surface pavement temperature (°C) and T_A = Ambient (air) temperature (°C).

Even if the air (ambient) temperature has no direct effect on the skid resistance, it affects the frictional properties of the tire rubber, which has a (weak) influence on the variation of skid resistance on the surface pavement [25,27,46,47]. An increase in the temperature of the tire rubber decreases the friction coefficient. Equation (5) presents tire temperature proportionally to the air and pavement temperature (Table 3).

$$\frac{SFC_t}{SFC_{25}} = 0.563 + \frac{45.9}{(t+8)} \qquad (R_2 = 0.83) \tag{5}$$

$$T_t = 12.3 + 0.48 * (Ta + Tp) \tag{6}$$

where SFC_t = the side force friction coefficient of the SCRIM (see Section 3) at tire temperature (T_t), T_t = tire temperature (°C), T_p = surface pavement temperature (°C) and T_A = ambient (air) temperature (°C).

Regarding the influence of the temperature on the skid resistance, the *SFC* is corrected, according to the temperature, by the following equation [48]:

$$SFC_{20°C} = SFC + (T - 20) * 0.007 \tag{7}$$

where:

SFC = the side force friction coefficient of the SCRIM at tire temperature (T_t);
$SFC_{20°C}$ = the side force friction coefficient obtained at 20 °C temperature;
T = surface pavement temperature (°C).

2.6.2. Impact of Rainfall

Rainfall is one of the factors that can cause short-term variation in the measurement of the skid resistance; adequate skid resistance can partially reduce the accident rates during the rainy period. Previous studies showed that the skid resistance decreases during the rainfall period, while the value increases after rainfall due to the less contaminated road pavement surface, which causes increased direct contact between the tire and the road surface [49]. However, some studies illustrate that the skid resistance decreases after 7 days of rainfall, which is due to the accumulation of the contaminate on the road surface [30] (see Table 3).

2.6.3. Impact of Snow and Ice/Freezing Conditions

The behavior of the friction generated by the tire–road surface interfaces is important during winter in order to ensure vehicle safety and control of driving tasks for road users. Moreover, the continuity of the snow makes the friction even more important, because

of the slippery road pavement surface—caused not only by the water film thickness but also as a result of the accumulated snow and low temperatures—that may cause icing or freezing of the road surface [50,51] (see Table 3). During snowing, the visibility of the road is poor, which can be an additional factor that influences driver behavior besides freezing of the road pavement surface.

On the other hand, two major factors could influence the frictional behavior caused by the tire and the road surface during snowy conditions, these being the temperature of the road surface and the speed range [52,53]. In light of the aforementioned mechanism, the frictional phenomenon reaches a higher temperature, which can be high enough to melt the surface and convert the snow layer/snow grains into water, and decrease the skid resistance [54,55]. Due to the presence of such unfavorable weather conditions as freezing and icing of the road surface, more research related to the investigation of the ice percentage and freezing points is needed to establish a traffic management procedure.

2.6.4. Impact of Contamination

The influence of the contamination on the pavement surface and the design of the aggregate mix has been discussed in various studies. The contamination layer between tire and road surface acts as a coating interface or thin direct-contact layer, which influences the direct contact of the tire and the road pavement. Contaminants are classified into different materials (dust, sand, oil, grease, grass, organic debris, rubber particles, organic materials produced as a result of accidents, chemical liquids, and other possible contaminants) as a form of lubrication on the surface pavement, which prevent reliable contact between the tires and the surface pavement [30,49]. This produces a decrease in skid resistance of the road pavement. Moreover, the contamination of wet surfaces was studied [19]: contamination materials such as water, oil, liquid, and sand salt material were applied in field case studies; the results presented a decrease in skid resistance due to the existence of contamination materials compared to the normal situation with a clean surface pavement for both rigid and flexible pavements. The average decrease in the skid resistance reached 48.6% in flexible pavements and 52.3% in rigid pavements due to the existence of the lubricant oil as a contamination material on the road surface [56]. Further studies are essential to provide a better understanding of the effect of each above-mentioned contaminant on the efficiency and skid resistance of the road pavements.

2.6.5. Impact of Wind

Wind speed can also be a factor that influences the coating of the surface pavement due to wet weather conditions or de-icing effects during extreme weather conditions in winter. A light wind/breeze may support the evaporation process of the existing moisture (or the solvent from cutbacks) on the road surface pavement [57]. In addition, in some zones, wind speed or storms can have a detrimental effect on skid-resistance due to the carrying of dust, or some random distribution of dust and other organic materials, on the surface pavement. Terminal serviceability could be recommended when there is dust/or a windy storm; at this stage, frequent monitoring of the skid resistance is recommended to ensure the safety of road users. Several techniques are frequently used to ensure pavement preservation. Seal coats are one of the major techniques that is usually applied to ensure the flexibility of road pavement preservation, and this technique could provide waterproofing, delays in aging, and enhancement of skid resistance. Wind speed may affect the functionality of the seal coat on the road pavement due to the dust, and other materials can have an impact during storms [57,58]. Wind observation increases the chances of reliable seal coat placement on road pavements. Very few studies focus on the effect of wind speed on skid resistance, although this is particularly essential during the coating process.

3. Skid Resistance Measurement Requirements and Methodologies

3.1. Skid Resistance Methodologies

Measurement of the skid resistance is a challenging task as the friction measurement of the tire–road interfaces could be influenced directly or indirectly by numerous man-made factors and natural factors (see Section 2). Moreover, the standard technique to measure skid resistance is considered on wet pavements [5,58,59]. Thus, dry and wet conditions of the pavement have a significant influence on skid resistance measurements. Data collection commonly contains errors of different types and magnitudes. These errors can be initiated by human contributions (e.g., visual rating, data classifications, data processing, or data entry) or the instrument or technology used. Nevertheless, data collection on skid resistance could be influenced by two main types of error: namely, a systematic error (data related errors) and a random error (irregular cases). In some cases, it is difficult to distinguish between the two errors, and many errors are a combination of both systematic errors and random errors [60].

Quite a few steps needed to be implemented to further understand the skid resistance:

- Set up a reliable skid resistance policy and set of guidelines across Europe and worldwide;
- Standardize feasible thresholds for traffic management procedures;
- Establish measurement techniques and parameters;
- Develop a common scale;
- Implement the developed techniques;
- Compare the results with other sensor-based and non-destructive techniques;
- Validate the results with other possible simulations, as well as with data analysis and machine learning;
- Conduct real-time monitoring through the application of novel technologies such as Building Information Modelling (BIM).

Various techniques are commonly used to measure skid resistance on pavement surfaces. Each technique has specific parameters, and the skid resistance measurement could differ slightly depending on the device used due to adverse aspects and parameters [28,31]. Generally, the classification of skid resistance is based on three categories:

1. Field techniques to measure in-situ skid resistance;
2. Laboratory tests based on samples taken from the site or designed for research purposes;
3. New technology-based techniques, namely contactless sensors to collect data covering various aspects, from surface pavements to environmental conditions, which can be used in large-scale laboratory experiments or directly in field-based case studies.

Five methodologies, based on the operational principles of skid resistance measurement, are commonly used in academia and industry. Table 4 presents the most frequent operation principles of the equipment used to measure the frictional coefficients between the tire–road interfaces.

Table 4. Measurement operation principles for skid resistance measures.

No.	Method-Operation Principles	Abbreviation	Description	Test Type	Reference
1	Longitudinal friction coefficient	LFC	Sliding process control of the tires using the braking force system.	Direct (contact or semi-contact) measurement	[27,30]
2	Sideway force coefficient	SFC	The ratio of the sideways force to the vertical force between the tire and the road surface.		[30,31]
3	Friction measuring equipment	CFME	Spatial variability of tire–pavement frictional properties.		[30,32]
4	Sliders or stationery or slow-moving measurement principles	Sliders	Using rubber sliders that are attached either to the foot of a pendulum arm or to a rotating head, which slow down on contact with the pavement surface. They are thus used in the lab and stationary tests.		[30,31]
5	Sensors-based methodologies (optical measurement system)	Sensors	Measurement of the pavement texture or ice percentage using an optical measuring system.	Indirect (contactless) measurement	[33,34]

Several methodologies are widely used to determine the skid resistance of the road pavement surface [61–65], which is based on different principles. Various output parameters are then concluded. Table 5 presents a detailed list of such methodologies, principles, main output parameters, and potential tire/wheel load properties. Hence, skid resistance measurement devices are usually available on the market, but some are not available for public or commercial use since the device in question was originally developed for a specific need, region or country.

Table 5. Simplified/summary list of friction/skid resistance measurement techniques.

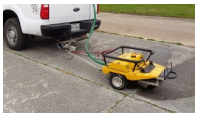
No.	Test Types	Device Name	Main Outputs/Parameters	Tire and Wheel Load	Device View	Employed in	Reference
A.			**Measurement principles based on Longitudinal Friction Coefficient (LFC)**				
A.1	Field-based test	ADHERA	Water film thickness: 1.0 mm; Measures macrotexture; Measurement speed: 40, 60, 90, 120 km/h; Measurement interval: 20 m	PIARC smooth profile tire 165R15 (180 kPa); Wheel load: 2500 N		France	[65]
A.2		BV-11	Slip ratio: 0.17 or 17%; Water film thickness: 0.5–1.0 mm; Measurement speed: 70 km/h; Measurement interval: 20 m	Trelleborg type T49 tire (140 kPa); Wheel load: 1000 N		England, Sweden, and Finland	[31]
A.3		GripTester	Slip ratio: 0.15 or 15%; Water film thickness: 0.5 mm; Measurement speed: 5–100 km/h; Measurement interval: 10–20 m or other	254 mm diameter smooth profile ASTM-tire (140 kPa); Wheel load: 250 N		United States, United Kingdom, and others	[36]
A.4		RoadSTAR	Slip ratio: 0.18 or 18%; Water film thickness: 0.5 mm; Measures macrotexture; Measurement speed: 30, 60 km/h; Measurement interval: 50 m	PIARC tire with tread; Wheel load: 3500 N		Australia	(modified from [66])
A.5		ROAR DK	Slip ratio: 0.2 or 20%; Water film thickness: 0.5 mm; Measures macrotexture; Measurement speed: 60, 80 km/h; Measurement interval: >5 m	ASTM 1551 tire (207 kPa); Wheel load: 1200 N		Denmark	[49]
A.6		ROAR NL	Slip ratio: 0.86 or 86%; Water film thickness: 0.5 mm; Measures macrotexture; Measurement speed: 50, 70 km/h; Measurement interval: 5–100 m	ASTM 1551 tire (200 kPa); Wheel load: 1200 N		Netherlands	(modified from [67,68])
A.7		RWS NL Skid resistance tailor	Slip ratio: 0.86 or 86%; Water film thickness: 0.5 mm; Measurement speed: 50, 70 km/h; Measurement interval: 5–100 m	PIARC smooth profile tire 165R15 (200 kPa); Wheel load: 1962 N		Netherlands	[37]
A.8		Skiddometer (BV-8)	Slip ratio: 100% or 14%; Water film thickness: 0.5 mm; Measurement speed: 40, 60, 80 km/h; Measurement interval: 30–50 m	AIPCR tire with longitudinal tread 165R15; Wheel load: 3500 N		Sweden	(modified from [66,67])
A.9		SRM	Slip ratio: 15% or 100%; Water film thickness: 0.5 mm; Measurement speed: 40, 60, 80 km/h; Measurement interval: 20 m or other	AIPCR tire with longitudinal tread 165R15; Wheel load: 3500 N		Germany	(modified from [68])

Table 5. *Cont.*

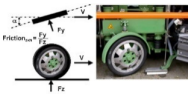
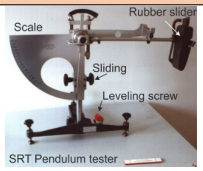
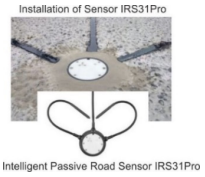
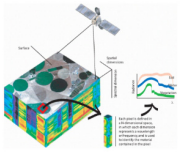
No.	Test Types	Device Name	Main Outputs/Parameters	Tire and Wheel Load	Device View	Employed in	Reference
A.10		TRT	Slip ratio: 25%; Water film thickness: 0.5 mm; Measurement speed: 40–140 km/h; Measurement interval: 20 m or other	Smooth profile ASTM tire; Wheel load: 1000 N		Czech Republic	[66]
A.11		SRT-3	Slip ratio: 100%; Water film thickness: 0.5 mm; Measurement speed: 60 km/h	Tire with tread (200 kPa)		Poland	[31,38]
A.12		IMAG	Slip ratio: 100%; Water film thickness: 1.0 mm; Measurement speed: 65 km/h	PIARC smooth profile tire; Wheel load: 1500 N		France	[31]
A.13		MU-Meter	Friction; Self-wet trailer	Three small-wheeled trailers; Wheel load: 250 N		Germany	[39]
B.			**Measurement principles based on slow-moving Longitudinal Friction Coefficient (LFC)**				
B.1	Laboratory and field-based test	T2GO	Slip ratio: 20%; Used for pedestrian/bicycle paths and road marking	Two 75 mm width tires		Switzerland	[31,40,67]
B.2		VTI Portable Friction Tester (PFT)	Used for pedestrian/ bicycle paths	Three small wheels		United Kingdom	[41]
C.			**Measurement principles based on Sideway Friction Coefficient (SFC)**				
C.1	Field-based test	SCRIM	Slip angle: 20°; Water film thickness: 0.5 mm; Measures macrotexture; Measurement speed: 50 km/h; Measurement interval: >10m	Avon SCRIM smooth profile tire 76/ 508 (350 kPa); Wheel load: 1960 N		United Kingdom, France, Germany, Netherlands, and New Zealand	(modified from [49])
C.2		(SKM) Skid resistance measure-ment method	Slip angle: 20°; Water film thickness: 0.5 mm; Measurement speed: 50 km/h; Measurement interval: 100 m or other	Smooth profile tire; Wheel load: 1960 N		Germany	(modified from [49])
C.			**Measurement principles based on Rotating Friction**				
D.1	Laboratory-based test	DFT Dynamic Friction Tester	For stationary measurements	-		Japan	[22]

Table 5. *Cont.*

No.	Test Types	Device Name	Main Outputs/Parameters	Tire and Wheel Load	Device View	Employed in	Reference
E.			**Measurement principles based on Pendulum test**				
E.1	Laboratory-based test	SRT Pendulum	For stationary measurements	-		Switzerland	(modified from [69])
F.			**Measurement principles based on optical measurement, and image-based techniques** [70–74]				
F.1	Sensors and contactless tests	MARWIS-Mobile Advanced Road Weather Information Sensor	Ambient surface temperature: −50–70 °C; Road surface temperature: −40–70 °C, ±0.8 °C @ 0 °C; Dew points: −50–60 °C; Road conditions: dry, moist, wet, snow, ice; Water film thickness: 0–6000 µm; Ice percentage: 0–100%; Rel. humidity: 0–100%; Friction (frequency of up to 100 times per second and a max. output rate of 10 Hz): 0–1	Installed on a back of a vehicle		Germany	(modified from [63])
F.2		Intelligent Passive Road Sensor IRS31Pro-UMB	Ambient surface temperature: −50–70 °C; Road surface temperature: −40–80 °C; Freezing point: −40–0 °C; Road conditions: dry, moist, wet, snow, ice; Water film thickness: 0–4 µm; Ice percentage: 0–100 %; Friction: 0–1	-		Germany	(modified [75])
F.3		LCMS Sensors	Measurement of macro-texture (MPD, MTD) Measurement of longitudinal prole and calculation of roughness Water-entrapment calculation Pavement type detection (asphalt, chip seal, porous, concrete) Slope, Cross Fall, and Super Elevation Friction Features related to damages	Installed on a back of a vehicle		Canada	(modified from [64,73])
F.4		SPECIM AisaFenix 1 K airborne system	Friction Can be used in various civil engineering applications	Airborne based Imaging spectroscopy method (hyperspectral imaging or spectral imaging)		Finland	[72,73]

Nowadays, a wide range of remote sensing techniques are applied in different civil engineering fields [45,74]. The use of the remote sensing techniques mentioned in Table 5 (group F) can be divided into three different categories:

F.1 MARWIS-Mobile Advanced Road Weather Information Sensor: This sensor is mounted with a vehicle, which turns the vehicle into the driving weather station to detect several critical road conditions and weather parameters (e.g., dry, wet, rain, snow, ice percentage, snow thickness, friction, pavement temperature, ambient temperature, humidity, and relative humidity). The distance between the sensor and the road surface must be in a range of 0.5–2 m. The working mechanism of the MARWIS sensor is based on infrared measurements; four transmitters and two receivers are used to capture the

reflected behavior of the road pavement surface [46]. Accuracy of the data is crucial in order to monitor real conditions using this sensor. Several factors can affect the accuracy of the data collection, which mainly include lightening, storms, extreme heat waves, tree shadows, road markings, manhole covers, and sensor warming time.

F.2 Intelligent Passive Road Sensor IRS31Pro-UMB: This sensor is a flush based sensor, which is mounted and fixed in the road pavement to detect various weather condition parameters based on the ice percentage of the road surface. Similarly, to the MARWIS sensors, it can detect different weather conditions on the pavement surface including dry, wet, ice, snow, rain, air temperature, pavement, friction, road conditions, humidity, and freezing point. The IRS31Pro-UMB sensor is based on the RS485 interface with a UMB protocol [46].

F.3 LCMS Sensors: An innovative 3D sensor for road inspection processes. LCMS is commonly used to inspect cracking on the road pavement surface by extracting a 3D profile of the road pavement. However, LCMS was employed to characterize the road pavement surface texture in various studies [47]. This sensor can significantly reduce labor costs and project completion times, with an overall accuracy of 1 mm in terms of resolution, within the range of 0 to 100+ km per hour, in automated pavement condition surveys conducted over the course of one day or night [64,73].

F.4. SPECIM system: This is a full spectrum hyperspectral camera, which is ideal for remote sensing of the environment and other aerial survey applications in civil engineering. The hyperspectral sensor features around 1024 pixels, and it enhances the productivity of hyperspectral imaging to a new level with a reduction in flight cost of 60% compared to other airborne sensors due to less flight lines being required. This method can be used to understand the road surface properties, with a wide range of up to 10 km^2 area at 1 m geometric standard deviation (GSD). However, SPECIM can also be used in various applications such as mines, soil characterization, and water contamination [72,73].

Minimum thresholds of skid resistance can be split into two categories, namely conceptual skid resistance threshold approaches, and current skid resistance thresholds. Both are described in the following sections.

3.2. Concept of the Skid Resistance Threshold Approaches

A possible threshold of skid resistance is based on the test procedures and test devices that can be adapted for specific roadway system needs. The above-mentioned factors (e.g., speed and water film thickness, etc.) influence the practice of traffic management systems in terms of skid resistance. Roadway authorities strongly recommend a specific standard of skid resistance for the practice of pavement management systems, as a threshold to be applied in rehabilitation and maintenance process [76–78]. Thresholds are commonly based on wet-weather conditions and compared to available skid resistance standards.

In addition, two procedures are commonly considered for skid resistance thresholds in road pavement systems, namely the investigatory level and the intervention level of skid resistance in management system procedures [77–80].

- **The investigatory level** is the level of the skid resistance threshold, according to which authorities and road pavement system owners have to take action in order to monitor the skid resistance and accident rates of highways for the purpose of furthering plans related to necessary preventive or/and maintenance work related to roadway systems.
- **The intervention level** is the level at which skid resistance is low due to various factors that influence the road pavement system; at this level, urgent action (e.g., maintenance, restoration, and rehabilitation processes) is strongly recommended to be taken by roadway authorities and owners to provide safe driving conditions for road users. If needed, an important action such as provisionally closing a specific section of highway for a certain period is essential to prevent high accident rates during wet conditions, since an urgent restoration process is required.

3.3. Current Skid Resistance Thresholds

Minimum skid resistance is essential to ensure the reliability of driving tasks. Since no robust analytical methodology is available, minimum skid resistance thresholds have been established by highway bodies based on various parameters including the deterioration level of the surface pavement, accident rates (particularly in wet conditions), expert knowledge, and practices established for similar conditions by other highway agencies. Three approaches are recommended to provide a reliable skid resistance threshold (Table 6).

Table 6. Summary of commonly used approaches for skid resistance (modified from [77]).

No.	Data-Based Approach	Description	Indication	Threshold Level
1	Historical SK Data	Plot of the historical SK deterioration data over time, which is based on the increase in the deterioration rate of SK.	SK magnitude or percentage	Intervention
2	AR and Historical SK Data	Plot of the historical SK deterioration data against time and AR, which is based on the increase in the deterioration rate of SK.	SK or increase in AR (crash level)	Intervention
3	SK Distribution and AR-SK spectrum	Calculation of the standard deviation of SK and the adjustment of this value with the AR ratio from wet-to-dry conditions.	SK and AR ratio based on wet-to-dry conditions.	Intervention

Note: (i) SK refers to Skid Resistance and (ii) AR refers to Accident Rate, respectively.

In the literature, several road pavement parameters are considered in order to identify the concept of minimum skid resistance, namely water film thickness or pavement texture properties. Thus, differences exist between the actual skid resistance and the measured one since the water film thickness is fixed on the testing side at a specific time (test time) and vehicle speed, but skid resistance changes along the highway section [81–83]. On the other hand, the accident rate can be quantified based on the accident numbers in a specific period, as well as the geometrical parameters of the roadway. Moreover, the above-mentioned approaches are based on a statistical analysis of historical data and accident rates, for which the task of investigating and identifying an actual factor or cause that can be considered as a threshold for traffic management system procedures is challenging due to the limitations caused by the wet-weather conditions, in addition to other possible factors (see Section 2). Table 7 presents minimum skid resistance intervention levels for various conditions.

Table 7. Standard skid number (SN), intervention level, and actions based on a commonly used device (SCRIM) (adapted from [26,83,84]).

No.	Skid Number (SN)	Intervention Level	Roadway Conditions	Required Action
1	<0.3	Weak	Any conditions	Urgent preservation
2	≥0.3	Low Acceptable	Low-volume traffic	Frequent monitoring
3	0.31–0.34	Acceptable	Normal-volume traffic	Habitual monitoring
4	≥0.35	High acceptable	Low-volume traffic	Investigation level

On the other hand, several other skid resistance intervention level thresholds are mainly applied in the USA, New Zealand, and England. Table 8 presents different minimum skid resistance thresholds used by different states in the USA, as well as those used in New Zealand and England.

Table 8. Minimum skid resistance intervention level thresholds in different countries (adapted from [79]).

No.	Skid Number (Sn) Intervention Level	Highway Organization	Roadway Conditions	References
1	SN40S [1] < 30	Idaho Dot	Normal highways	[49,50,84]
2	SN40R [1] < 30	Illinois Dot	Normal highways	
3	SN40R < 28	Kentucky Dot	Normal highways	
4	SN40R < 32	New York Dot	Normal highways	
5	SN40R < 30	Texas Dot	Normal highways	
6	SN40R < 32	Ohio Dot	Normal highways	[85]
	SN40S < 23			
7	SN40R < 30	Maryland State Highway Agency	Undivided highways	[86]
	SN40R < 25		Divided highways	
8	Low Skidding Crash Risk—ESC [2] < 0.30	New Zealand Transport Agency	Low-volume traffic	[87]
	Medium Skidding Crash Risk—ESC < 0.30		Normal-volume traffic	
	High Skidding Crash Risk—ESC < 0.35		High-volume traffic	
9	CSC [3] < 0.30	England Highways	Motorways: Low-volume traffic	[88]
	CSC < 0.35		Motorways: Heavy-volume traffic	
	CSC < 0.40		One-way and Two-way traffic	
	CSC < 0.45		Minor and major junctions	
	CSC < 0.50		High-risk situations; Pedestrian crossings	
	CSC < 0.55		High-risk situations; Pedestrian crossings	
	CSC < 0.60		High-volume traffic	
	CSC < 0.65		High-volume traffic	

[1] SN40R and SN40S are the skid numbers measured at 64 km/h (40 mph) using the ASTM standard method e274 for rib tire and smooth tire, respectively (See [84]). [2] ESC is the equilibrium SCRIM Coefficient computed as normalized (seasonally corrected) SCRIM coefficients for both within-year and between-year variations. The SCRIM coefficient is the skid resistance measured at 50 km/h by skid testing machine SCRIM (British Standard 2006) (See [85]). [3] CSC is a Characteristic SCRIM Coefficient computed from measured SCRIM coefficients corrected for the effect of seasonal variation. The SCRIM coefficient is the skid resistance measured at 50 km/h using the SCRIM skid testing machine (British Standard 2006) (See [88]).

4. New Trends and Future Research

New trends in road infrastructure management are widely proposed and discussed in research studies, with the consideration of new models as decision support tools to facilitate the necessary action for road management procedures. In this section, the main focus is on the new trends and current projects related to the skid resistance management of the surface. This section consists of two main aspects, which are the challenges commonly faced by data analysts in relation to data treatment, as well as the accuracy and precision of information, after the stage of data collection from sites. In addition, a current European research project on the assessment of infrastructure, based on a particular deliverable related to the management of roadways, is discussed, which presents a methodology of establishing a set of thresholds for the skid resistance of the road surface pavements and traffic management procedures.

4.1. Challenges in the Skid Resistance Data Analysis and Interpretability

In the past, different approaches were developed to elaborate on the concept of skid resistance, but no proper model could gather the maximum possible parameters, which would involve both skid resistance stability and measurement. These are based on three main parameters of transportation systems, including pavement texture, tire properties, and other environmental influences integrated with the surface pavement texture [5,8,83,88–90]. Data obtained from different methodologies must be treated with an appropriate analytical approach to achieve a better understanding of skid resistance. In light of this, data analysis and consolidation are highly significant as they enable an increase in the interoperability of advanced knowledge and uses of data. Infrastructure design begins with the engineering design stage, followed by the validation phase, then, during service life, inspection data and on-site service are considered in order to increase human safety and facilitate an optimal lifecycle of the structure. In addition, several new technological approaches (e.g., sensors) are commercialized, with the undertaking of research, to provide advanced knowledge on surface pavements. Sensors are smart tools for big data collection that consider real-time data, which could be used for further data analysis and provide an automatic alert for various applications. Smart sensors are not only able to measure the physical properties of the pavements, but can also create big data and transmit data sets through the internet based on the implementation of the Internet of Things (IoT) to provide traffic management procedures as a supporting tool for decision-making owners [91].

In this section, approaches to increase the accuracy of the data interoperability, intelligent data analysis, and some of the significant challenges and new directions in the field of skid resistance measurement are discussed:

- Since the 1990s, Artificial Neural Network approaches (ANN) have been widely applied with machine learning algorithms for maintenance prediction problems including those related to the condition or life expectancy of transport infrastructure assessments (particularly in road pavements). In traditional ANNs, not only are the selection of training algorithms and optimal model architectures challenging; they are also time-consuming training processes and the instability of skid resistance models, in terms of local minimum points, limits the performance of the models and/or their validation [92].
- Numerical modeling (e.g., the finite-difference time-domain method (FDTD)) of various parameters involved in the skid resistance of the surface pavements is essential in two contexts: (a) The design of possible surface pavements and the further understanding of skid resistance before any experimental sample designs or sample scans are produced. (b) Simulated data or synthetic data can be a significant tool to support the validation of the results from laboratory or field case studies. Numerical modeling can be also used as a complementary methodology for integration with analytical approaches in order to advance the existing knowledge on skid resistance [15–19].
- Application of Building Information Modelling (BIM) [93]: results from processed analytical models or sensors could be integrated with BIM models (e.g., IFC models, 3D Spatial models, or integrated approaches) to provide real-time monitoring of skid resistance, to ensure a reliable decision-making tool for skid resistance of the surface pavement, and to support traffic management procedures.
- To overcome the current challenges, a rapid inspection approach is strongly recommended to provide reliable action requirements for repairs, maintenance, and traffic management procedures. Augmented Reality (AR) [94] can be an efficient approach to provide on-site 3D real monitoring of dynamic roadway system environments.
- Most studies focus on highway roads and interstate highways for skid resistance assessment, and there are a few studies on rural roadways. Henceforward, the accuracy and precise prediction of the skid resistance in roadways is still a challenge [95–97]. Further studies are essential to overcome Road Infrastructure (RI) assessment challenges with new methodologies and approaches.

4.2. PANOPTIS Project and Current Developments

The current European H2020 research project "PANOPTIS-development of a decision support system for increasing the resilience of transportation infrastructure based on the combined use of terrestrial and airborne sensors and advanced modeling tools" [95] aims to leverage current knowledge and tools that can be integrated to establish a new solution for Road Infrastructure (RI) assessment during periods of multi-hazard resilience [96–98].

In this project, one of the parameters to be analyzed is skid resistance and the related effects on surface road pavements, which can directly influence the driving task and operation of the roadway network system. The PANOPTIS project aims to provide the operators and owners with an integrated tool that is capable of supporting efficient traffic management procedures, planning, operation levels, rehabilitation, and urgently required actions. Thus, the project is designed to use actual data obtained from various sensors and data treatment methodologies. The skid resistance deliverables are comprised of two main stages:

- The first stage of the project is data collection by two main road sensors, namely MARWIS (the Mobile Advanced Road Weather Information Sensor), based on the macrotexture of the surface pavements, and the IRS31Pro-UMB Intelligent Passive Road Sensor, based on the ice percentages of climate changes on the surfaces of pavements, which consists of two passive sensors in different sections: PK83 and PK103 (see Figure 4). This project is implemented on a demo case study section of the Spanish A2 Highway that connects two major cities in Spain, which is the public highway between Madrid with Barcelona. Operation and maintenance are managed by the Concessions Division of the ACCIONA. The Spanish site is selected due to the potential influence of the weather at this location, which can cause severe infrastructure damage, such as damage to bridges. The highway length is about 77.5 km; it is located in the province of Guadalajara, consists of four lanes (two per traffic direction), and crosses a Continental–Mediterranean climate region with long, severe winters, and dry, hot summers [96] (see Figure 5). Climate Change is based on an increase in the maximum temperature in summer (~5 °C by the end of the century) and a decrease in minimum temperature in winter (~3 °C by the end of the century).
- The second stage of the project is to develop an advanced tool to monitor the changes and skid resistance of the surface pavement of roads, which is mainly affected by weather conditions such as water content on the road surface due to rainfall, ice, and also seasonal changes in the temperature. Thus, these conditions can influence the traffic management procedures through the standardization or establishment of a robust analysis of the skid resistance thresholds against other parameters of the traffic system to minimize accident rates, or/and increase safe driving task for road users.

Information and outputs are obtained from both of the above-mentioned sensors, and the developed models and applications used on the Spanish demo site will be integrated and processed through a unique Resilience Assessment Platform that will support operators in the introduction of adaptation and mitigation strategies based on multi-risk scenarios.

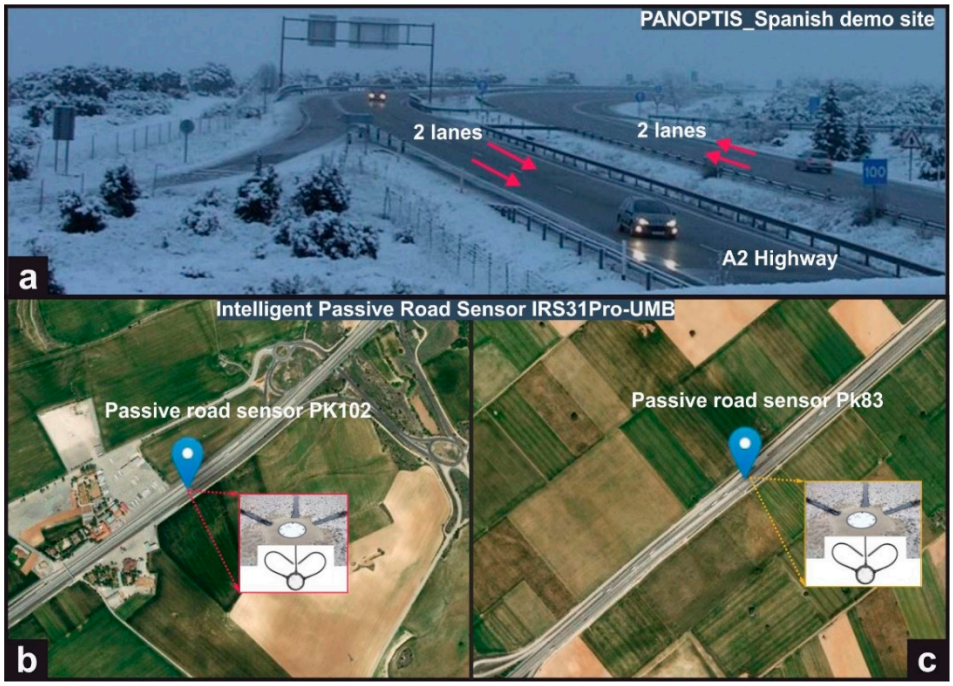


Figure 5. View of A2 Highway and zones where ice-sensors are installed in Spain. (**a**) View of the Spanish demo site (Guadalajara) A2-section 2 in between Madrid and Barcelona (modified from [96]). (**b**) A2 highway section where the PK102 ice-sensor is installed (shown in red color) (modified from Panoptis, 2021). (**c**) PK83 ice-sensor installed in a section of the A2 highway (shown in red yellow color) (modified from [95–98]).

4.3. TYROSAFE Project

TYROSAFE is European research project funded by the European Community's Seventh Framework Programme (FP7/2007–2013) under grant agreement no. 217920 [99]. The TYROSAFE project's main aims are to raise awareness, promote coordination and prepare a harmonization at the European scale in order to optimize the assessment and management of essential tire/road interaction parameters for the purpose of increasing safety and supporting the greening of European road transport. The project was focused on various aspects of road surfaces, including tire properties and tire–road interaction. TYROSAFE has provided a synopsis of the current literature of the scientific community, as well as national and European standards related to road surfaces.

In the framework of the TYROSAFE research project, a research plan and an outline of future needs are given, with respect to national and European road agencies, in order to optimize three main properties: skid resistance, rolling resistance and tire/road noise emission. Furthermore, the outcomes of this project have been extended to a new European project called ROSANNE [100] to speed up the European harmonization and standardization of regulations surrounding the skid resistance, noise emission and rolling resistance of road pavements.

5. Discussions and Conclusions

Safe and reliable pavements are of paramount importance for both human losses and economic growth, especially with the vast growth of traffic systems. An appropriate pavement design should take into account these aspects. In the context of this review of studies related to the skid resistance on the surface pavements, it is possible to draw the following conclusions:

- The current state-of-the-art in skid resistance measurements techniques is illustrated while highlighting new sensor-based methodologies.

- A list of factors that influence the skid resistance of the surface pavement is given. More particularly, the effect of the environmental conditions such as rainfall, snow, ice, contamination, temperature, and wind are elaborated upon.
- Skid resistance requirements and the concept of the standardization, minimum acceptable levels, thresholds, and necessary action are discussed.
- New trends in methodologies and data treatment, and new challenges, are elaborated upon.
- Current research projects are considered, which are related to tasks that deal with the skid resistance of pavement surfaces and traffic management procedures.

In conclusion, as the knowledge of skid resistance can be modified with consideration of several factors including man-made factors and natural hazards or weather conditions, PANOPTIS will be a very valuable tool for road infrastructure (RI) assessment and for furthering the understanding of pavement surfaces. Despite the current state of the art and available models, methodologies, and case studies concerning skid resistance, it is necessary to carry out further research, mainly using novel data analysis approaches, to understand seasonal changes in weather conditions, correlation of temperatures and other environmental conditions with skid resistance, and possible thresholds, in order to support the traffic management authorities to ensure the safety of road users and to increase economic growth. Finally, several suggestions are offered to stakeholders, road managers, road owners, the sensor industry, the vehicle industry (e.g., tires companies), and coating solution agencies.

- Better choices of pavement mixtures;
- The development of new pavement mixtures;
- An appropriate link between factors (such as tires or environmental conditions) and skid resistance;
- Better traffic management: speed limits, distances between vehicles, interdiction of vehicles;
- Better road management (maintenance, repair of surfaces, and improvement of coating methods);
- Better road usage (de-icing salt, optimization of sustainable environmental solution).

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