


## Article

# Analysis of the Skid Resistance Decrease in Bituminous Pavements in Dual-Carriageway Tunnels

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**Abstract:** Unlike other pavement indices, the skid resistance, or friction, of bituminous pavements behaves differently. After the extension of a new layer, the friction increases as the bitumen film is removed and the aggregates are exposed. The aggregates are then polished by traffic, mainly by heavy vehicles, and the pavement reaches the seasonal phase, in which, if heavy traffic volume remains constant, the only variations are seasonal, with maximum values in winter and minimum values in summer. Nonetheless, in tunnels, as they are not exposed to climatic actions, the friction value is lower than outside. Therefore, the article evaluates the skid resistance decrease in tunnels compared to outdoor conditions. For this purpose, the skid resistance values in dual-carriageway tunnels in Gipuzkoa (Spain) were studied and compared with the values obtained 500 m before and after the tunnel. Overall, a 10% friction decrease was observed inside the tunnels. In winter, the decrease was 11%, while in summer it was 8%. In tunnels longer than 500 m, the decrease was greater (12%) than in tunnels shorter than 500 m (9% and 7%). This analysis contributes to a better knowledge of the available friction inside a tunnel and to the better management of road safety.

**Keywords:** skid resistance; pavement friction; tunnel; road safety; SCRIM coefficient; pavement management system



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## 1. Introduction

Despite efforts to reduce the number of injuries and fatalities in road crashes, road safety remains a serious problem, being the leading cause of premature death worldwide [1–5]. In general, crashes are due to multiple causes, which are often grouped into driver-related, vehicle-related, and road condition-related, in varying proportions [6–8].

With regard to road conditions, numerous studies showed that there is a significant relationship between crash risk due to sliding and skid resistance in both dry and wet conditions [9–14]. For example, Page and Butas [15] found that crash rates on wet pavements was higher on curves, especially those with a transverse skid resistance lower than 0.25. Indeed, some of the most potentially dangerous driving conditions arise from low friction due to heavy rainfall combined with poor road geometry, or from sudden changes in skid resistance, which may be caused by contaminants, localized surface defects, or the initial moments of precipitation [16]. Musey and Park [17] found that great injuries occurred on curves with higher degrees of curvature and lower friction. Comparing conditions before and after, Lyon and Persaud [18] measured a reduction in accidents of up to 57% on sections and junctions with a high proportion of accidents related to wet pavement and low friction. In Spain, Mayora and Piña [19] showed a 68% reduction in wet pavement crashes by increasing the skid resistance from an average SCRIM coefficient value of 50 to 60, measured by the Sideway Coefficient Routine Investigation Machine (SCRIM).

Skid resistance, or pavement friction (used synonymously for this paper), is defined as the “force that resists the relative rotation between a vehicle wheel and the pavement” [6]. The force is generated when the vehicle wheel rotates or slides on the road surface and is the result of a complex interaction between adhesion and hysteresis [3,20–22]. Adhesion appears at the contact between the wheel and the pavement and is related to the roughness of the aggregate at the micro level, i.e., the micro-texture of the pavement. Hysteresis is attributed to irregularities at the macro level of the surface, the macro-texture of the pavement [22–24]. The scales of surface texture were defined at the XVII World Road Congress in 1987 in Brussels (Belgium) [25] as a function of wavelength ( $\lambda$ ) and amplitude (Table 1).

**Table 1.** Classification of pavement deviations.

Level of Texture	Wavelength, $\lambda$	Amplitude, A (mm)
Micro-texture	$0 < \lambda < 0.5$	$0.001 < A < 0.5$
Macro-texture	$0.5 < \lambda < 50$	$0.1 < A < 20$
Mega-texture	$50 < \lambda < 500$	$1 < A < 50$
Roughness or unevenness	$\lambda > 500$	$1 < A < 200$

Micro-texture depends on the surface properties of the aggregates and the bituminous material that binds them and macro-texture on the properties of the bituminous mix, such as shape, size, and gradation of the aggregates. While micro-texture and macro-texture are necessary properties for friction, mega-texture and surface regularity should be avoided. Factors affecting the skid resistance of pavements are usually grouped into four categories [6,23,25–30], as shown in Table 2.

**Table 2.** Factors affecting road friction.

Pavement Surface Characteristics	Vehicle Factors	Tire Properties	Environment
<b>1. Micro-texture</b> <b>2. Macro-texture</b> <b>3. Material properties</b> 4. Mega-texture/unevenness 5. Temperature	<b>Slip speed</b> , as a function of 1. Vehicle speed 2. Slip ratio 3. Driving maneuver 3a. Turning 3b. Overtaking	<b>1. Tread design and condition</b> <b>2. Inflation pressure</b> 3. Rubber composition and hardness 4. Foot print 5. Load 6. Temperature	<b>1. Temperature</b> <b>2. Water</b> (rainfall, condensation) <b>3. Snow and ice</b> <b>4. Contaminants</b> (salt, sand, dirt, mud) 5. Wind

Note: Key factors in each shown in bold.

On the other hand, there are numerous skid resistance measurement devices and equipment, which are usually classified according to three principles of operation: longitudinal friction coefficient, transverse friction coefficient, and sliding (stationary or low speed) [31,32]. The SCRIM, developed by the Transport and Road Research Laboratory (TRRL) in the UK, consists of a truck chassis with a standardized wheel arranged at a fixed oblique angle at 20 degrees to the longitudinal axis of the vehicle, and connected to a constant water supply. When the truck moves forward, the test wheel rolls but slides in the longitudinal direction due to the angular difference. The standardized test speed is 50 km/h. The Side Force Coefficient (SFC), measured with the SCRIM, is the ratio of the sideways force to vertical reaction between the pavement surface and the tire, ranging from 0 to 1. A SCRIM reading, SR, is the direct output of each subsection measured in the road, with usual lengths of 5, 10, or 20 m, obtained as the average SFC value at the entire subsection, expressed as an integer value, and multiplied by 100. The SR values are obtained directly from the SCRIM and must be corrected for speed. The SCRIM coefficient, SC, is the SR value corrected for speed and machine variability, expressed as a decimal fraction, with two decimal figures. This is the equipment used in Spain to measure the skid resistance of a pavement [33]. In the Spanish standard, SC values were expressed as

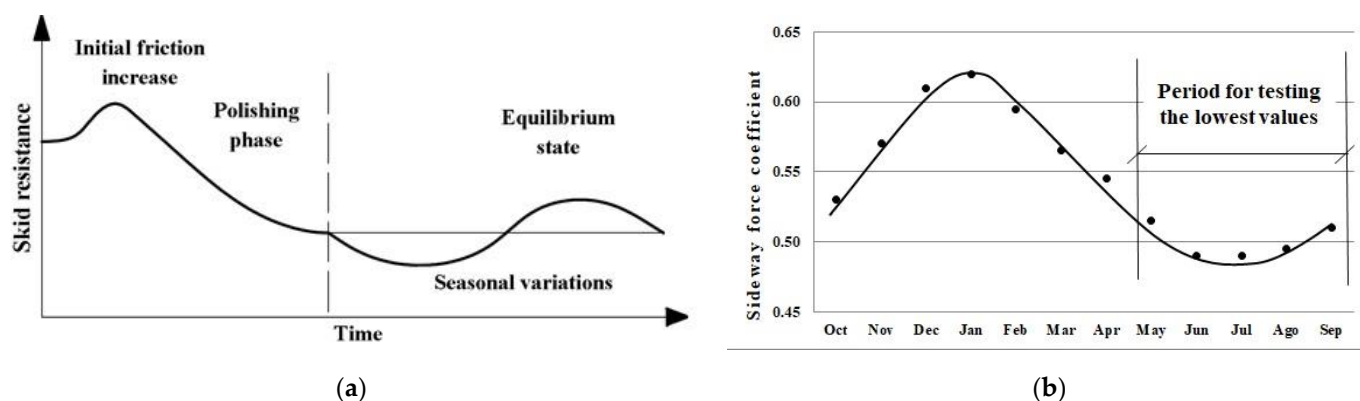
a decimal fraction, ranging from 0 to 1 [34]. However, from 2001, it is indicated that SC values must be expressed from 0 to 100, i.e., multiplied by 100 [35].

Nevertheless, in each test, each skid resistance measuring procedure follows the established standards, mainly with regard to tire properties, vehicle speed, slip ratio, water supply ratio, etc. Consequently, once a road administration has selected a standard to obtain the pavement friction on the road network it manages, the surface characteristics of the pavement and environmental factors are the only variables that affect the results, while the rest of the variables indicated in Table 2 remain constant (approximately) [36].

As mentioned above, the surface characteristics of the pavement that affect friction include macro-texture and micro-texture [23,37–42]. Macro-texture depends on the maximum aggregate size, the type of the coarse and fine aggregate, the gradation of the aggregates, the voids content of the mix, and the bituminous binder. Micro-texture depends only on the type of coarse aggregate, especially through the Polished Stone Value (PSV) [31,43–45].

With regard to environmental factors, water is a key factor in skid resistance [46,47]. On dry and clean surfaces, high friction values are achieved. However, when the road surface is slightly wet, like at the onset of rainfall, a significant reduction in available friction is observed as the water film on the surface acts as a lubricant between the tire and the pavement and also reduces the contact area. This is why most friction tests are performed on wet surfaces. Regarding contaminants, there is a wide range (including snow, ice, dust, clay, loose gravel, sand, and vehicle contaminants such as fuels and oils) [12,30,48] that interfere with friction mechanisms and reduce friction values. However, the individual effect of each contaminant has not been researched [49]. Finally, except in extreme conditions, temperature does not significantly affect the friction of bituminous layer aggregates. However, since both tires and bituminous materials are viscoelastic, they are more sensitive to temperature changes [50]. As a rule, an increase in temperature leads to a decrease in skid resistance.

In terms of pavement age, the behavior of friction differs from that of other pavement properties, which typically worsen over time and with traffic [51–54]. An internationally accepted model describes the evolution of skid resistance over time (Figure 1a) [55–57]. For new bituminous pavement, an initial increase in friction is observed as the bitumen film overlying the aggregates is removed. This value reaches its maximum once the bitumen film has disappeared and the aggregates are exposed to traffic, providing high friction due to their micro-texture. Once the aggregates are directly exposed to traffic, they undergo the usual polishing process [23,58], leading to a decrease in the friction value until an equilibrium phase is reached, where skid resistance tends toward an asymptotic value [59,60].



**Figure 1.** (a) Evolution of skid resistance over time; (b) seasonal variations in skid resistance in equilibrium phase during year.

Previous research has shown that, if traffic volumes are maintained, fluctuations during the equilibrium phase are primarily due to seasonal variations and other short-duration factors. However, there is no consensus on the duration of these phases. In Spain,

the initial increment usually lasts between 2 and 3 months, although in some cases, due to the strength of polymer-modified bitumen, it can take up to 4 years [61]. Different durations have also been reported for the polishing phase, ranging from 4 or 5 years [49] to 1 year [55,62].

Seasonal variations in skid resistance, observed during the equilibrium phase, have been documented since 1931 [63], with the lowest values measured in summer and the highest in winter (Figure 1b). On dry roads, particularly in summer, the polishing action of traffic is dominant; however, when pavements remain wet for extended periods, usually in winter, the surface regains some of its previous texture and hardness [64]. The magnitude of these variations primarily depends on the geological history and petrography of the aggregates used. The first study on these seasonal variations was conducted in the UK [65], involving pavements in a seasonal state and collecting friction data monthly for 11 years (1958–1968) (Figure 2).

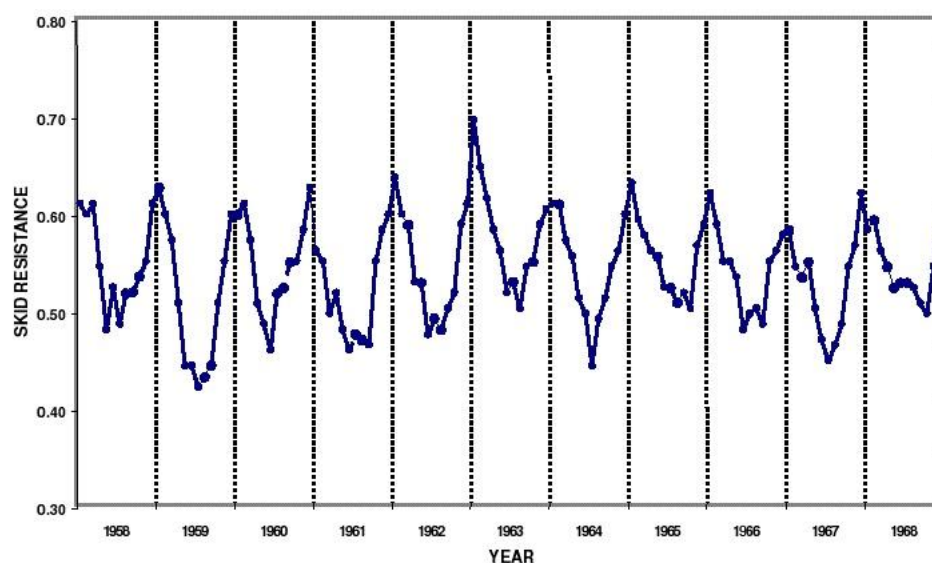
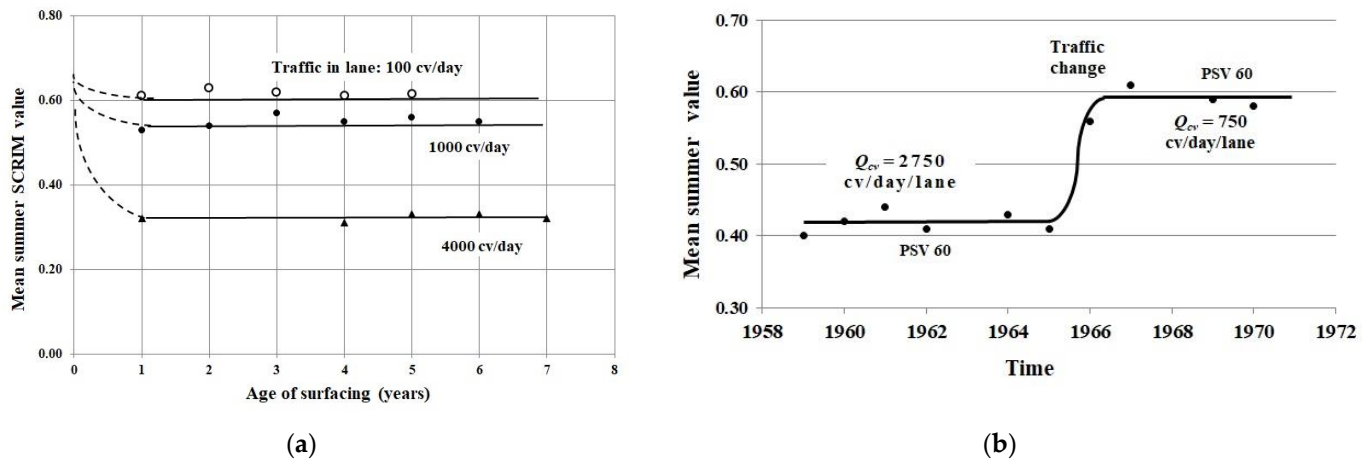


Figure 2. Skid resistance measured in UK for 11 years with SCRIM.

Other studies in other countries also certify these seasonal variations [62,66,67]. For pavements in the stationary phase, differences between years are related to changes in climate, but are less important than seasonal variations. Sinusoidal models are commonly used to model these variations [66,68].

The polishing intensity of aggregates in the polishing phase is directly related to traffic intensity, and especially to the intensity of heavy traffic [69,70]. Kennedy et al. [71] indicated that, with all other conditions being equal, a road with a higher volume of heavy traffic would have a minimum skid resistance value since it is responsible for the polishing of the aggregate micro-texture. Figure 3a shows this idea with data from the UK with aggregates with PSV between 58 and 60 [72]. As seen, the initial decrease is due to the polishing phase but does not continue after reaching the equilibrium phase. Therefore, heavy traffic should not be considered year on year as a cumulative value, as it only depends on the annual intensity of heavy traffic [60]. Even when heavy vehicle traffic has dropped drastically, for example, due to a bypass of that section, increases in friction have been observed both in the UK [73] (Figure 3b) and in Spain on the N-VI in León (Spain) [74].

Nonetheless, seasonal variations do not occur in the tunnels. Since they are not exposed to the wet periods of winter, they are not subject to seasonal variations and therefore the aggregates do not recover their macro-texture. Hence, as dirt accumulates, as in dry periods in open-air sections, and is not washed away by rain, the values of skid resistance are lower inside the tunnels than outside [75,76]. Lower values have also been observed in tunnels with cement concrete pavements [77]. Therefore, lower skid resistance values were identified as a key factor for traffic accidents in tunnels [78–80].



**Figure 3.** Average SCRIM coefficient values in summer: (a) with heavy traffic volume; (b) with change in heavy traffic volume.

Although these lower values are known inside tunnels compared to the values observed in the open air, the decrease in slip resistance inside tunnels has not been quantitatively evaluated. Therefore, the aim of this article is to quantify the difference between the SC obtained inside a tunnel and the values outside the tunnel. For this purpose, the SC values measured in dual-carriageway tunnels with bituminous pavements in the road network of the province of Gipuzkoa, in Spain, were studied and compared with the values recorded 500 m before and after the tunnel, where the same type of material is present in the surface layer.

## 2. Literature Review

Due to the importance of pavement skid resistance on road safety, many studies have investigated the available friction in each phase based on different characteristics. Wang et al. [81] replicated the skid resistance evolution shown in Figure 1a with some plates from a test track polished using the Aachen Polishing Machine. The bitumen removal and the polishing action on aggregates were described with a five-parameter friction model. In addition, at the final polishing stage, the available skid resistance tended to be an asymptotical value. Xie et al. [82] presented a self-developed accelerated polishing machine to simulate the process with real tires and analyzed the behavior of fine aggregate polishing susceptibility (FAPS) by means of the British pendulum number (BPN). They demonstrated that the final BPN tends to a value asymptotically and the FAPS is a measure of the rate of the skid resistance decrease. Similarly, evaluating the friction of eight different hot mix asphalt (HMA) mixtures, Khasawneh [83] showed that friction decrease was higher during the first hour of polishing and stabilizes with time, resulting in an asymptotical value. Yan et al. [84] also corroborated the asymptotical trend on ultra-thin asphalt overlays after sufficient abrasion cycles. The seasonal variations experimented by the friction during the equilibrium phase has also attracted interest. With data from six roads in Texas, Jayawickrama and Thomas [66] presented various skid prediction models using sinusoidal functions to represent seasonal variations. Similarly, Echaveguren and Solminihac [68] developed models for the oscillatory pattern by considering a fixed wavelength adjusted to a calendar year.

Other researchers presented some skid resistance prediction models based on aggregate properties. Goulias and Awoke [85] identified the proportion of the aggregate blend, some gradation characteristics of the aggregates, and the asphalt binder grade employed in the HMA as the predictors of the amount of Equivalent Standard Axle Loads that the pavement can support before an established minimum friction. Taking data from twenty-two testing places, with various treatments and aggregates in Oklahoma, Li et al. [86] tried to correlate thirty-one 3D aggregate texture parameters, grouped in four categories

(textural, feature, height, and material ratio and volume parameters) with measured skid resistance. Eight parameters were selected based on their statistical significance, with the entropy and peak curvature as the most significant influencing factors on friction. In fact, the employment of 3D laser images is becoming a new method for evaluating skid resistance [5]. Moreover, other authors studied how to improve the available friction by means of new mixing designs [20,87] and after incorporating new materials, such as crumb rubber bitumen [88], steel slag [89–91], and calcined bauxite aggregates [42,92].

One of the most challenging problems with pavement skid resistance is correlating laboratory and field results. Hofko et al. [93] established correlations between polishing simulation carried out with a Wehner/Schulze device and traffic loads in real roads. In a first step, at Texas A&M University, Rezaei et al. [94] related the International Friction Index (IFI) with some aggregate properties and a number of polishing cycles in the laboratory. In a subsequent step, Rezaei and Masad [95] presented an IFI prediction model based on traffic volume instead of polishing cycles, showing again the exponential decrease to an asymptotical value, as shown in Figure 1.

A further challenge in this field is to predict the available minimum skid resistance in a real road as a function of data from real pavements. One of the first models was developed by Szatkowski and Hosking [73], where the mean SCRIM coefficient measured in summer was predicted as a function of the Polished Stone Value (PSV) and the daily volume of commercial vehicles (those with a mass over 1500 kg). This model was considered as a major achievement in the field of skid resistance at that time [72]. In New Zealand, a model was presented with the same variables (PSV and average daily volume of commercial vehicles) but achieved very low accuracy ( $R^2 = 0.28$ ); however, it could be increased to  $R^2 = 0.43$  if the chip size was included [96]. Another study in New Zealand developed a model that added the average least dimension of the sealing chip to the previous variables [97]. Later, an incremental model was also proposed, in which the friction depended on the cumulated light vehicles, the type of asphalt, and local conditions [98]. Using data obtained in winter from 23 road segments, Pérez-Acebo et al. [36] developed a model for two-lane roads predicting the minimum friction in summer based on the average annual daily traffic of heavy vehicles (those weighing more than 3500 kg) and the required PSV according to the standards, after assuming a decrease from winter to summer. Later, a more complete model for any type of road was presented [57], including the AADT, the number of lanes in each direction, the material on the surface layer, and the required PSV. Santos et al. [99] showed some models for flexible pavements as a function of traffic, climate conditions, and other road characteristics. A more recent study presented two models for motorways in Bavaria based on the AADT of all vehicles, the AADT of heavy vehicles, and the number of lanes in the carriageway and, if it was available, the type of material at the surface layer [60]. All these models have shown that the number of vehicles (heavy, light, or both) has a direct impact on available skid resistance as it acts as an aggregate polisher. Efforts have been conducted to develop an equivalence factor that could correlate the polishing effect of heavy and light vehicles [56,100,101].

As seen, apart from traffic volumes, which directly affects the polishing rate, climate factors also influence available skid resistance, with minimum values in summer and maximum in winter. Nonetheless, there are certain sections where seasonal variations do not occur: inside the tunnels [102]. As tunnel segments are not exposed to the wet periods of winter, they are not subjected to seasonal oscillations and hence the aggregates cannot recover their macro-texture. Additionally, dirt is accumulated and is not washed away by rain as in open air spaces. As a result, lower friction values are observed in tunnels [103]. Notably, segments in tunnels exhibit higher crash frequency than segments outside the tunnels [104]. Ding et al. [78] showed the direct relationship between the lower skid resistance in tunnels and the higher ratio of accidents in tunnels.

Unlike asphalt pavement, concrete pavement is completely nonflammable and non-toxic in the case of a fire accident in a tunnel and hence concrete pavement has become a usual solution for pavements in tunnels [76,102]. However, as for bituminous pavements,

friction in tunnels is lower in cement concrete pavements than outside [105,106] due to the closed environment, car exhaust being prone to accumulate, and higher braking frequency [102,107]. Hence, after 3–5 years in service, the skid resistance is under the required minimum, creating a hazard for road safety [78]. Consequently, various techniques must be applied to guarantee minimum friction in concrete tunnels. Cleaning regularly with water may be a solution but the most effective methods are remaking the anti-skid structure and the asphalt overlay [108]. Coarsening techniques include grooving [108–110], milling [111], fine milling, brooming [110], exposed concrete pavement and polymer-modified cement concrete [102], and porous concrete [106]. Some asphalt overlay techniques include micro-surfacing [89], laying sealing layer [112], and asphalt concrete ultra-thin overlay [113–115].

In asphalt pavements in tunnels, the decrease in skid resistance has also been certified. Maurer et al. [103] conducted an analysis in Austrian tunnels. Measurements after new layers were extended and one year later were taken and it was shown that skid resistance was nearly constant. However, it was observed that values inside the data were lower, even with the same pavement type and constructed by the same contractor, gradually decreasing with the length of the tunnel. Friction values in the entire Austrian road network and values in the tunnels were compared, representing the cumulative frequency of the skid resistance data. A high percentage of the sections inside the tunnels were below the established minimum friction value in Austria. Additionally, a trend to obtain lower values in longer tunnels was observed. From the project, it was seen that, in general, lower values were measured in tunnels than outside for concrete and asphalt pavement, and some methods were proposed to improve the friction: cleaning with water, high pressure water (jetting, bullet, sand blasting), blasting, and suction of the removed brushed fine surface. Other techniques have also been investigated in asphalt pavement tunnels, such as water pressure and sweeping, to maintain the hydroblasting procedure conducted before [75].

As shown in this literature review, the lower friction in tunnels is certified in both concrete and asphalt pavements. However, the usual decrease that we can expect inside the tunnels is not clear. It is necessary to know the difference in SC points that can be expected in the SC points between both zones, and the expected average friction decrease in percentage. Moreover, there are still some questions needing to be answered. For example, as we know that there is seasonal variation outside the tunnel, is the friction difference between the outside and inside of the tunnel higher in winter or in summer? Furthermore, is there a direct relationship between the length of the tunnel and the measured friction? In other words, are lower values obtained in longer tunnels? Additionally, since the heavy vehicle traffic volume is said to be correlated with lower friction values, is the skid resistance difference higher with higher heavy vehicle volumes? The paper aims to answer these questions after analyzing 73 tunnels in the province of Gipuzkoa, in Spain, comparing values inside and outside tunnels in motorways with asphalt pavements. Specifically, for motorways in Gipuzkoa, a BBTM (béton bitumineux très mince) mixture is established as the unique possible solution. Observed differences between the data inside and outside the tunnels are analyzed.

### 3. Analyzed Sections and Methodology

#### 3.1. Analyzed Sections

The data to conduct this study on the decrease in the skid resistance in tunnels were obtained from the Regional Government of Gipuzkoa (RGG). Due to the special political status of the Autonomous Community of the Basque Country, each of the regional governments of the three provinces that compose the region (Bizkaia, Gipuzkoa, and Alava/Araba) has exclusive competence over the existing roads within its territory, except for municipal roads [116]. Thus, neither the Spanish Government (through the corresponding Ministry) nor the Basque Government has any competence over roads, and the RGG is responsible for managing even those roads belonging to itineraries, which run through more than one region or which belong to cross-border itineraries.

The data provided indicate the exact KP of their measurement and the length of the measurement section (10 or 20 m). The collecting data campaigns were carried out in different years (2005, 2007, 2010, 2015, 2018, 2021, and 2022), although not the entire network was surveyed in each of these years. The measurements were conducted in different months of the year, both in winter (January) and summer (June, July, and September), as well as in October and November. Most of the data were obtained using SCRIM [117], as described in the previous section. Additionally, some data collections were performed using the GripTester, which is a device equipped with a partially locked longitudinal measuring wheel (15%), with a fixed sliding degree, following the UNE-CEN/TS 15901-7:2010 IN standard [118]. The Grip Number (GN) obtained from these measurements can be correlated with the SC using Equation (1), proposed by the Transportation Research Laboratory (TRL) of the United Kingdom (former TRRL), with a correlation coefficient of 0.9701.

$$SC_{SCRIM}(\%) = \frac{0.89 \cdot GN}{0.78} \quad (1)$$

where  $SC_{SCRIM}$  is the SC value obtained using the SCRIM truck, expressed as a percentage, i.e., from 0 to 100; and GN is the Grip Number obtained using the Griptester.

As there are only two short tunnels in single carriageway roads in Gipuzkoa, it was decided to only analysis the tunnels in motorways, where there are more than forty. The high-capacity network in Gipuzkoa has a bituminous surface. Due to the high performance required for these roads, the usual bituminous mixes are draining mixes (type PA) and discontinuous mixes (type BBTM). Given that draining mixes can pose an additional risk in tunnels, since the high permeability of the material would allow a flammable liquid to spread rapidly across a large surface area, only discontinuous BBTM mixes are employed in dual-carriageway tunnels in Gipuzkoa, as specified in Basque Country's pavement design standard [119]. In addition, Gipuzkoa is a small province with a homogeneous climate, the oceanic climate. Hence, all the data are analyzed for a unique climate area.

### 3.2. Methodology

With the data described above, the following values were calculated:

- $SC_{tunnel}$ : The average of the recorded SC values within the tunnel's length.
- $SC_{before}$ : The average of the recorded SC values in the 500 m before the start of the tunnel.
- $SC_{after}$ : The average of the recorded SC values in the 500 m following the end of the tunnel.
- $SC_{ext}$ : This is the average of the  $SC_{before}$  and  $SC_{after}$  values and indicates the average value in the surroundings of the tunnel, considering the values before and after the tunnel (at the same distance of 500 m in each case).
- Absolute Difference,  $Diff(ABS)$ : This is the algebraic difference between  $SC_{tunnel}$  and  $SC_{ext}$ , which will have a negative value (due to the higher value of  $SC_{ext}$ ), according to Equation (2), and represents the difference in terms of CRT between inside and outside the tunnel.

$$Diff(ABS) = SC_{tunnel} - SC_{ext} \quad (2)$$

- Percentage Difference,  $Diff(\%)$ : This is the percentage of the absolute difference in the SC value outside the tunnel ( $SC_{ext}$ ), according to Equation (3), and represents the percentage decrease in the friction value in the tunnel compared to that outside the tunnel.

$$Diff(\%) = \frac{Diff(ABS)}{SC_{ext}} = \frac{SC_{tunnel} - SC_{ext}}{SC_{ext}} \quad (3)$$

A length of 500 m before and after the tunnel was considered as a valid length for assessing the friction conditions outside the tunnel. Shorter distances may influence the value due to local particularities, while longer lengths may contain different materials in the wearing course, which would introduce errors in the comparison.

Additionally, before data evaluation, cases where rehabilitation or maintenance activities have been carried out on the tunnel section and its outer parts were excluded. All the sections considered in the study are sufficiently aged to be regarded as being in a seasonal state, with the only fluctuations in skid resistance attributed to seasonal variations. Sections with younger pavements are still in the phase of increasing friction or accelerated polishing (Figure 1a), so their values should not be used. Usually, if the pavement is in one of these phases, the  $SC_{tunnel}$  and  $SC_{ext}$  values are similar, and in some cases, the SC values inside the tunnel may even be higher than those outside. These invalid data were removed from the analysis.

In addition to the previously mentioned data, the following information about the tunnel was also included:

- The name of the tunnel.
- Direction of the carriageway, indicated as ascending or descending, according to the Kilometer Points (KP).
- The length of the tunnel.
- The Annual Average Daily Traffic (AADT) of the segment.
- The Annual Average Daily Traffic of heavy vehicles in the project lane, the lane with the highest number of heavy vehicles (AADT-HV). In Spain, a vehicle is considered heavy when its mass exceeds 3500 kg [120].
- The traffic category according to the Spanish standard 6.1-IC [120].
- The month of the data collection.

Using the obtained values and grouping the tunnels according to various characteristics (tunnel length, traffic categories, and the season in which the measurement was taken), the following average values have been calculated:

- Average SC in the tunnel,  $\overline{SC_{tunnel}}$ : The average of the  $SC_{tunnel}$  values of the tunnels considered in that category.
- Average outdoor SC,  $\overline{SC_{ext}}$ : This is the average of the  $SC_{ext}$  values of the tunnels considered in that category.
- Mean Absolute Difference,  $\overline{Diff(ABS)}$ : This is the average of the  $Diff(ABS)$  values of the tunnels considered in that category.
- Average of Percentage Differences,  $\overline{Diff(\%)}$ : This is the average of the percentage differences,  $Diff(\%)$  of the tunnels considered in that category.
- Difference in Averages, in Percentages,  $Diff(AVER)$ : This is the ratio between the mean of the absolute differences and the mean of the SC values outside of the tunnels considered in that category, expressed according to Equation (4).

$$Diff(AVER) = \frac{\overline{Diff(ABS)}}{\overline{SC_{ext}}} = \frac{\sum_{i=1}^n (CRT_{tuni} - CRT_{exti})}{n \cdot \overline{SC_{ext}}} \quad (4)$$

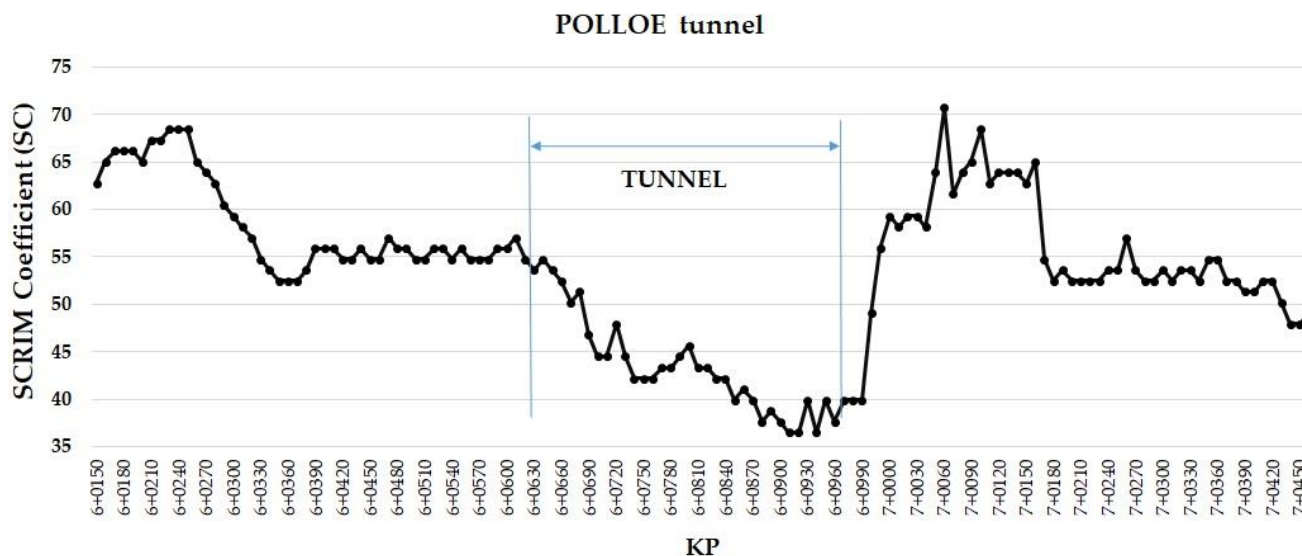
Although these last two values,  $\overline{Diff(ABS)}$  and  $Diff(AVER)$ , are similar, they are not the same, and it was considered convenient to calculate both in order to obtain a clearer picture of the variations between the SC values inside and outside a tunnel.

In addition, the mean differences of  $\overline{Diff(ABS)}$  between the established categories were tested to evaluate the significance of the difference for independent samples. In the case of comparing two categories, a two independent sample *t*-test was carried out, using either pooled variance (in the case of equal variance) or separate variance (in the case of unequal variance), as followed in other similar after-before analysis [121,122]. When comparing three categories, an Analysis of Variance (ANOVA) was made to test the mean difference between the categories, as in other research [123,124]. Previously, a Levene test was conducted to check for variance equality. In the case of equal variance, the DMS statistic was used to check the mean difference between the two categories individually. If the variance was unequal, the Tamhane's statistic test was employed for verifying the significance of the mean between the two categories.

#### 4. Results and Discussion

Using the methodology presented in Section 2, a total of 123 tunnels were available, which after discarding those sections in which maintenance and rehabilitation works had been carried out in previous two years and which therefore did not ensure that the pavement was in the equilibrium phase (Figure 1a), a total of 73 tunnels were obtained for the analysis. The minimum age for pavements in Gipuzkoa for reaching the equilibrium phase was established according to previous work on the topic in another province [62].

The appearance that is repeated in the tunnels observed is similar to that shown in Figure 4, which shows the SC values of the Polloe tunnel, on the GI-20, in ascending direction, measured in November 2018.



**Figure 4.** SCRIM coefficient values in Polloe tunnel, ascending KP, on GI-20 motorway, in November 2018.

It can be seen that the values outside the tunnel are clearly higher than those recorded inside. Inside the tunnel, the first few meters in the direction of travel have a friction similar to that outside the tunnel, but this decreases progressively along the length of the tunnel. This is due to vehicles introducing water from outside into the tunnel in the direction of travel (or due to the slope of the tunnel itself), until the wheels dry out inside. Additionally, dust and other contaminants deposited on the road surface cause the aggregates to be polished, but they do not regenerate during wet periods, as is the case outside the tunnel.

Table 3 shows the average values obtained considering all the tunnels analyzed. The mean value of the absolute difference between the values inside and outside the tunnel is more than 5 SC points (5.104), representing a difference of 10% compared to the mean SC value outside. The average percentage of the difference for each tunnel is similar, at approximately  $-10\%$  ( $-9.721\%$ ). Thus, there is an average decrease of 10%. RAs seen, tunnels in Gipuzkoa repeated the trend observed in other tunnels around the world, where lower friction values are observed inside the tunnel [102,103].

**Table 3.** SCRIM coefficient differences in all tunnels.

No. of Tunnels	$\overline{SC}_{tunnel}$	$\overline{SC}_{ext}$	$\overline{Diff(ABS)}$	$\overline{Diff(\%)}$	$\overline{Diff(\%)}$
73	45.838	50.942	-5.104	-9.721%	-10.02%

The data were grouped according to the season in which the data were collected to find out whether this decrease in the SC value inside the tunnel is constant throughout the year. If so, it would imply that the sinusoid that could represent the variation over the year

in a segment (Figure 1b) decreases uniformly inside the tunnel. Table 4 shows the data classified into winter (for data taken in January), summer (for data taken in June, July, and September), and autumn (for data taken in October and November).

**Table 4.** The SCRIM coefficient differences in the tunnels according to the season of the year.

Season	No. of Tunnels	$\overline{SC}_{tunnel}$	$\overline{SC}_{ext}$	$\overline{Diff}(ABS)$	$\overline{Diff}(\%)$	$\overline{Diff}(\%)$
Winter	17	51.837	58.455	−6.618	−11.55%	−11.32%
Autumn	34	42.249	47.273	−5.024	−10.13%	−10.63%
Summer	22	46.747	50.805	−4.058	−7.68%	−7.99%

It can be seen that the difference is greatest between the values inside and outside the tunnel during the winter, with a percentage difference in more than 11%. In autumn, this difference drops to just above 10%, while in summer, it reaches its lowest value, less than 8%. These trends are logical; in winter, the road surface recovers part of its skid resistance due to environmental factors, leading to the highest SC values [66,68]. However, these effects do not occur inside the tunnel, which explains the greater difference. During the summer and in periods of low rainfall, the outer road segments are not cleaned by rain, and pollutants, especially dust, are accumulated on the surface of the pavement, so friction is low. The same phenomena occur inside the tunnel, making the conditions in both sections similar [106].

Additionally, the ANOVA test indicated that there was equality of means between the groups ( $p$ -value = 0.110) and the Levene statistical analysis showed homogeneous variance, with a  $p$ -value of 0.314. However, the DMS statistical analysis showed that, when comparing the available three seasons, there is a significant difference between skid resistance differences in winter and in summer (Table 5). Autumn appears as an intermediate season between the other two.

**Table 5.** Multiple comparison of mean absolute difference between seasons.

Statistic	Group (I)	Group (J)	Mean Difference (I – J)	Std. Error	Sig.	95% Confidence Level Lower	Upper
DMS	Winter	Summer	−2.5603	1.202	0.037	−4.958	−0.162
	Winter	Autumn	−1.5942	1.106	0.154	−3.800	0.612
	Summer	Autumn	0.9661	1.019	0.346	−1.066	2.998

As seen, the seasonal variations also have an impact on the friction decrease in tunnels [67]. With a lower difference in summer, it can be said that tunnel conditions are nearer to those inside the tunnel.

If the data are analyzed considering only two climatic seasons, winter and summer, assigning the October data to summer and the November data to winter, according to the usual climatology in the area, Table 6 is obtained.

**Table 6.** SCRIM coefficient differences in tunnels in winter and summer.

Season	No. of Tunnels	$\overline{SC}_{tunnel}$	$\overline{SC}_{ext}$	$\overline{Diff}(ABS)$	$\overline{Diff}(\%)$	$\overline{Diff}(\%)$
Winter	39	45.203	51.042	−5.839	−11.12%	−11.44%
Summer	34	46.566	50.826	−4.261	−8.12%	−8.38%

Again, Table 6 underlines that the difference between the values inside and outside the tunnel during the rainy season, winter, exceeds 11%. This is higher than the one observed during the dry season, summer, which is slightly above 8%.

A  $t$ -test of the absolute difference between summer and winter was conducted to check if there was a significant mean difference between the seasons (Table 7). The results

indicated a mean difference between the two seasons with a confidence level of 92.2%, reinforcing the idea that there is a higher skid resistance difference in winter than in summer.

**Table 7.** Levene statistic for homogeneous variance and *t*-test for mean equality of absolute differences between summer and winter.

Levene Statistic		Mean Difference	<i>t</i> -Test for Mean Equality		Mean Difference	Std. Error
F	Sig.		t	d. o. f.		
1.943	0.168	Equal variance assumed	−1.802	71	−1.578	0.875

As previously indicated, the analysis about seasonal differences is exclusively referred to as the oceanic climate, which is the unique climate in the province. In other climates, different values may be observed.

Taking into account the lengths of the tunnels of the high-capacity network in Gipuzkoa, the following classification was made in order to have a similar number of tunnels in each group. Short tunnels were defined as those shorter than 100 m. Medium tunnels were those between 100 and 500 m long. Tunnels longer than 500 m were classified as long tunnels. Table 8 shows the average values obtained for each of these three groups.

**Table 8.** SCRIM coefficient differences in tunnels according to tunnel length.

Tunnel Length	No. of Tunnels	$\overline{SC}_{tunnel}$	$\overline{SC}_{ext}$	$\overline{Diff}(ABS)$	$\overline{Diff}(\%)$	$\overline{Diff}(\%)$
Short ( $l < 100$ m)	24	46.034	49.663	−3.628	−6.90%	−7.31%
Medium ( $100 < l < 500$ m)	19	44.746	49.502	−4.756	−9.37%	−9.61%
Long ( $l > 500$ m)	30	46.372	52.876	−6.504	−12.20%	−12.30%

From Table 8, it can be seen that the length of the tunnel plays an important role in the difference between the skid resistance values inside and outside the tunnel. As mentioned in Figure 4, at the beginning of the tunnel, due to the introduction of water particles by vehicles, or due to the existing slope of the section, rainwater from outside enters the tunnel in the first few meters. As a result, the SC values are higher at the beginning and decrease as it goes forward in the tunnel. This progression is logical, and it means that in the first few meters of the tunnel, the road surface conditions are similar to those of the open-air sections. This phenomenon was also observed in other asphalt tunnels [103]. Consequently, the short tunnel sections have a higher percentage of their length affected by this phenomenon and therefore the difference between the outside and inside is smaller. On the other hand, as the length of the tunnel increases, these initial meters, which can reach 30–40 m, or even 100–200 m in some cases, do not represent such a large proportion and therefore the difference is greater [103]. There are larger sections of 10 or 20 m that are subjected to tunnel conditions, with low SC values. Wang et al. [104] showed that crashes were most likely to happen in long tunnels. The lower available friction on this type of tunnel may be a reason for this higher probability. An increase in skid resistance means a decrease in crash frequency [79,80].

Furthermore, these results were statistically evaluated (Table 9). The ANOVA between the categories established based on tunnel length revealed that there is significance mean difference in the absolute difference ( $p$ -value = 0.017) and the Levene statistic showed that the variances were homogeneous ( $p$ -value = 0.125). The DMS statistical analysis showed that there is a significant difference between the absolute difference between the short and the long tunnels, while relationships with the medium-length tunnels are not significant. This fact reinforces the idea that tunnel length has a great influence on available skid resistance, decreasing the skid resistance with longer tunnels [103]. The medium-length tunnels act as an intermediate position between the two extreme positions.

**Table 9.** Multiple comparison of mean absolute difference between tunnel lengths.

Statistic	Group (I)	Group (J)	Mean Difference (I – J)	Std. Error	Sig.	95% Confidence Level	
						Lower	Upper
DMS	Short	Medium	1.128	1.113	0.315	−1.093	3.349
	Short	Long	2.876	0.993	0.005	0.895	5.856
	Medium	Long	1.748	1.063	0.105	−0.373	3.868

Finally, friction differences were analyzed according to the traffic category, established on the basis of the AADT-HV in the year in which the friction measurement was carried out. The traffic categories are those set out in the Spanish standard 6.1-IC [120], shown in Table 10. Table 11 shows the differences in skid resistance for each of the categories.

**Table 10.** Traffic categories according to Spanish standard.

Traffic Category	Heavy Vehicles/Day <sup>1</sup>	Traffic Category	Heavy Vehicles/Day <sup>1</sup>
T00	≥4000	T31	200 > hv/day ≥ 100
T0	4000 > hv/day ≥ 2000	T32	100 > hv/day ≥ 50
T1	2000 > hv/day ≥ 800	T41	50 > hv/day ≥ 25
T2	800 > hv/day ≥ 200	T42	25 > hv/day

Note: <sup>1</sup> Heavy vehicles/day in lane with highest number of vehicles.

**Table 11.** SCRIM coefficient differences in tunnels according to traffic category.

Traffic Category	No. of Tunnels	$\overline{SC}_{tunnel}$	$\overline{SC}_{ext}$	$\overline{Diff(ABS)}$	$\overline{Diff(\%)}$	$\overline{Diff(\%)}$
T00	9	43.049	45.907	−2.858	−5.80%	−6.23%
T0	17	45.753	50.448	−4.695	−8.98%	−9.31%
T1	39	46.586	52.165	−5.579	−10.58%	−10.70%
T2	8	45.508	51.689	−6.181	−11.53%	−11.96%

It can be observed that in the higher traffic categories, the difference between tunnel and outside is smaller, around 6% in category T00, and 9% in T0, while values above 10% and 11% are obtained in categories T1 and T2, respectively. However, this trend should not be interpreted in a straightforward way, but should be taken with caution, since out of the 9 tunnels included in the T00 category, 7 of them are less than 100 m long, and the other 2 are 269 and 315 m long. As seen in Table 8 and Figure 4, the length of the tunnel is a value that greatly affects the available friction inside the tunnel. In the case of the tunnels in the T0 category, 9 have a length of less than 100 m and the other 9 are no longer than 500 m. It is worth noting that the value of  $\overline{SC}_{ext}$ , which does not depend on the length of the tunnel, is lower for the higher categories (T00 and T0), while it is higher for the lower categories. Although measurements were taken in different months of the year, the results shown in Figure 3a [73] align with this observation.

Moreover, the ANOVA test indicated that there was no mean difference between the absolute differences in the traffic categories ( $p$ -value = 0.203) and the Levene statistical analysis showed that the variances were homogeneous ( $p$ -value = 0.168). Nevertheless, the DMS statistical analysis indicated that there were significant mean difference in the absolute difference between some traffic categories (Table 12). More specifically, the differences between T00 and T1, and between T00 and T2 are almost significant since their  $p$ -values are 0.053 and 0.072, respectively. Nonetheless, as previously commented, the values obtained for each traffic category are highly biased by the length of the tunnels. From this analysis, conclusions cannot be deduced.

**Table 12.** Multiple comparison of mean absolute difference between traffic categories.

Statistic	Group (I)	Group (J)	Mean Difference (I – J)	Std. Error	Sig.	95% Confidence Level	
						Lower	Upper
DMS	T00	T0	1.837	1.544	0.238	−1.242	4.917
	T00	T1	2.721	1.385	0.053	−0.041	5.483
	T00	T2	3.329	1.819	0.072	−0.307	6.953
	T0	T1	0.884	1.088	0.420	−1.287	3.055
	T0	T2	1.485	1.605	0.358	−1.717	4.688
	T1	T2	0.602	1.453	0.680	−2.2975	3.501

## 5. Conclusions

In this study, the difference between the inside and outside of a tunnel was analyzed. For this purpose, the transversal skid resistance values, by means of the SCRIM coefficient (SC) measured inside the tunnels were compared with the values recorded 500 m before and after the tunnel. The data come from 73 tunnels in the road network of the province of Gipuzkoa (Spain), which are in the equilibrium phase, and the only fluctuations in the friction value are due to seasonal variations.

The analysis showed that there is an average difference of 10% between the value inside and outside the tunnel. This average value varies according to the season of the year. In winter, when the friction values outside the tunnel are highest, the difference is more than 11%. In contrast, during summer, when the friction values are lowest, the difference is around 8%.

Furthermore, tunnel length was identified as an important factor influencing the friction measured inside. Short tunnels, less than 100 m in length, show only a 7% difference in skid resistance. Tunnels between 100 and 500 m exhibit differences exceeding 9%, while those longer than 500 m show differences in more than 12%. Regarding the classification of tunnels by traffic category, smaller differences were noted in the higher categories (T00 and T0), while larger differences were observed in the lower categories (T1 and T2). However, it is important to note that most of the tunnels in categories T00 and T0 are short (less than 100 m), which influences the results.

Additionally, it must be noted that these findings are limited to a specific asphalt pavement surface, BBTM, and unique environmental conditions, an oceanic climate region. In other circumstances, with other climate factors and other asphalt pavements results may vary.

With respect to these data, it is important to take into account the lower skid resistance inside road tunnels, so road administrations should consider complementary actions to increase safety by increasing the available friction. In addition, tunnels represent critical points in any road network, making the issue of friction reduction particularly significant. The influence of this lower skid resistance values in tunnels could be further investigated as an affecting factor on road safety in tunnels in Gipuzkoa.

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