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APLICACIÓN DE PARÁMETROS DE MACROTEXTURA Y FRICCIÓN EN LA GESTIÓN DE PAVIMENTOS PARA LA SEGURIDAD VIAL

APPLICATION OF MACROTEXTURE AND FRICTION PARAMETERS IN PAVEMENT MANAGEMENT FOR ROAD SAFETY

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Resumen

El estudio abordó mejoras en la seguridad vial mediante la integración de parámetros de macrotextura y fricción en un Sistema de Gestión de Pavimentos (PMS). El objetivo fue desarrollar y validar un marco que armonizara mediciones heterogéneas mediante el Índice Internacional de Fricción (IFI), estableciera umbrales operativos y produjera una priorización orientada al riesgo de intervenciones dirigidas a la pérdida de resistencia al deslizamiento. Se aplicaron procedimientos de adquisición estandarizados (perfilometría 2D/3D para MPD/ETD y mediciones de fricción continua/puntual), junto con controles de QA/QC, un flujo de trabajo ETL, conversión a IFI (ASTM E1960), estratificación por clase funcional y clima, y derivación de umbrales mediante análisis ROC/percentiles; la priorización se realizó con un esquema multicriterio (condición, exposición, coste y beneficio esperado). Los resultados mostraron series de IFI trazables por segmento, umbrales diferenciados por tipología de carretera y una lista jerarquizada de secciones críticas consistente con los registros de exposición y accidentes, lo que permitió una programación más efectiva de los tratamientos de conservación. Se concluyó que la integración propuesta permitió tomar decisiones reproducibles y auditables, enfocando los recursos donde el impacto esperado en la reducción del riesgo es mayor; se recomendó la calibración local de coeficientes y la incorporación progresiva de métricas 3D y series de tiempo para fortalecer la predicción y el monitoreo operativo.

Palabras clave: Macrotextura; Fricción; IFI; Gestión del pavimento; Seguridad vial.

Abstract

The study addressed improvements in road safety by integrating macrotexture and friction parameters into a Pavement Management System (PMS). The objective was to develop and validate a framework that harmonised heterogeneous measurements via the International Friction Index (IFI), established operational thresholds, and produced a risk-oriented prioritisation of interventions targeting loss of skid resistance. Standardised acquisition procedures were applied (2D/3D profilometry for MPD/ETD and continuous/spot friction measurements), together with QA/QC controls, an ETL workflow, conversion to IFI (ASTM E1960), stratification by functional class and climate, and threshold derivation using ROC/percentile analyses; prioritisation was performed with a multicriteria scheme (condition, exposure, cost, and expected benefit). The results showed traceable IFI series by segment, differentiated thresholds by road typology, and a ranked list of critical sections consistent with exposure and crash records, enabling more effective

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programming of preservative treatments. It was concluded that the proposed integration enabled reproducible and auditable decisions, focusing resources where the expected impact on risk reduction is greatest; local calibration of coefficients and the progressive incorporation of 3D metrics and time series were recommended to strengthen prediction and operational monitoring.

Keywords: Macrotexture; Friction; IFI; Pavement management; Road safety.

1. Introduction

Road safety is severely compromised under wet-pavement conditions, where the loss of adhesion between the tyre and the road surface significantly increases crash risk. Various studies have shown that approximately 20% of traffic accidents occur during rainfall, with pavement skid resistance being a determining factor in the occurrence of such incidents (fawzy et al., 2024; Fwa, 2017). The reduction in friction, caused by the presence of water and the diminution of surface macrotexture, limits vehicles' ability to brake and manoeuvre safely, especially at higher speeds or in emergency situations (Cai et al., 2024; Najafi et al., 2017). In addition, the accumulation of water on the carriageway can generate hydroplaning, in which contact between tyre and pavement is completely lost, resulting in total loss of vehicle control (Spitzhüttl et al., 2020).

The problem is exacerbated on road sections with unfavourable geometry, worn surfaces, or insufficient drainage, where the incidence of skid-related crashes is even higher (Li et al., 2025; Pitaksringkarn et al., 2018). Evidence shows that decreasing friction values are directly correlated with increased wet-pavement crash rates, and that improving adhesion can reduce such incidents by up to 68% (Lyon et al., 2018; Pardillo & Jurado, 2009). However, the management and assessment of skid resistance present challenges, since traditional methods do not always consider variables such as rainfall intensity, vehicle speed, or the irregular distribution of water over the surface (Cai et al., 2024; Fwa, 2017). Therefore, it is essential to establish appropriate macrotexture and friction parameters within Pavement Management Systems

(PMS) in order to identify and treat high-risk sections as a priority and thus reduce crash frequency associated with loss of adhesion on wet pavements (McCarthy et al., 2022; Pitaksringkarn et al., 2018).

The development of regulatory and methodological frameworks for pavement management and evaluation has been led by international organisations such as PIARC, TRRL, and ASTM. PIARC (World Road Association) has promoted global guidelines for assessing safety and surface performance of pavements, while the United Kingdom's TRRL (Transport and Road Research Laboratory) has been a pioneer in research on the relationship between macrotexture, friction, and crash occurrence, establishing widely adopted measurement methods and safety thresholds. For its part, ASTM has standardised procedures such as ASTM E274 for friction measurement and ASTM E965 for macrotexture, as well as the use of the Pavement Condition Index (PCI) for comprehensive assessment of pavement condition (Loprencipe et al., 2017).

The integration of these frameworks and parameters into Pavement Management Systems has evolved towards multicriteria models that consider not only structural and functional condition, but also safety, sustainability, and vehicle operating costs (Khahro et al., 2021). Recent experiences show that incorporating indicators such as IFI and PCI into PMS enables the prioritisation of interventions based on the risk of loss of adhesion and crash occurrence, optimising resource allocation and improving road safety (Abu Dabous et al., 2020; Loprencipe et al., 2017). Moreover, the current trend is towards automation and digitalisation of data collection, as well as the application of multicriteria analysis methodologies for prioritising critical sections, integrating friction, texture, traffic, and sustainability variables in the comprehensive management of road networks (Abu Dabous et al., 2020).

Scientific evidence shows that reduced friction on wet pavements increases both the probability and severity of crashes, hence managing macrotexture and friction as operational variables in PMS is critical for prioritising interventions with a road-safety criterion. Reviews and empirical studies maintain that improving skid resistance is associated with substantial accident reductions, and that the friction–accident relationship persists after controlling for geometry and operation, for example with continuous devices such as SCRIM and seasonal correction methodologies (Fwa, 2017).

In parallel, the PIARC, TRRL, and ASTM frameworks have consolidated protocols to measure and harmonise texture and friction, for example ASTM E274 for locked-wheel testing and the International Friction Index (IFI). This enables inter-equipment and inter-network comparability, which is indispensable for integrating thresholds and risk maps into asset management (ASTM International, 2020; PIARC, 2009). Methodologically, recent literature recommends combining texture metrics (MPD/ETD) and friction (F60/BPN or continuous) with exposure to risk (traffic, climate, speed), and employing multicriteria prioritisation approaches within PMS, which have shown improvements in transparency and efficiency of preservative programming compared with schemes based solely on traditional structural or functional condition (Kumar et al., 2023).

Objective. To develop and validate an integration framework for macrotexture and friction parameters within a PMS oriented towards road safety, which: (i) harmonises measurements via IFI to ensure inter-equipment comparability; (ii) establishes operational thresholds and risk maps by functional class and climatic setting; and (iii) implements a multicriteria prioritisation scheme, including condition, risk, cost, and expected benefit, for scheduling preservative and corrective treatments, with traceability to PIARC, TRRL, and ASTM standards and recent practices in safe pavement management.

The article is structured into four parts: Conceptual and Regulatory Framework, which sets out the foundations of macrotexture and friction, IFI, and PIARC, TRRL, and ASTM guidelines; Materials and Methods, describing integration into PMS, including data acquisition and quality control, conversion to IFI, indicators and thresholds, risk mapping, and multicriteria prioritisation; Results, presenting the application at network and project levels, validation of the safety module, sensitivity analysis, and the intervention plan; and Conclusions, which synthesise contributions and recommendations for institutional implementation in Latin American contexts.

2. Materials and Methods

2.1. Methodological design and integration into the PMS

The study applied a quantitative and applied approach, aimed at integrating macrotexture and friction parameters within the Pavement Management System (PMS) for road safety purposes.
The methodology was organised into three main stages:

- **Measurement:** acquisition of texture and friction data at network and project levels using standardised equipment.
- **Conversion and harmonisation:** standardisation of results to the International Friction Index (IFI) to ensure comparability between equipment and conditions.
- **Integration into the PMS:** incorporation of the converted parameters into a functional assessment module that enables the identification of sections with adhesion deficits and the prioritisation of their treatment.

The methodological structure was designed to ensure coherence, traceability, and compatibility with institutional PMS inspection and maintenance procedures, without modifying its operational architecture.

2.2. Data sources and data acquisition

Primary and secondary data were used and integrated into a georeferenced database linked to the PMS.

Primary data:

- **Macrotexture:** determined by 2D/3D profilometry in accordance with ISO 13473-1, and by the volumetric sand patch method (ASTM E965) at verification points.
- **Surface friction:** obtained using water-filled wheel devices (ASTM E1911 / EN 13036) and, at specific locations, with the British Pendulum Tester (ASTM E303).

Secondary data:

These included annual average daily traffic (AADT), percentage of heavy vehicles, operating speed (V85), climatic conditions (precipitation and temperature), road geometry, and records of crashes on wet pavements.

Sampling was conducted by homogeneous segments defined according to functional class and climatic setting. Each measurement was georeferenced using GNSS, with density proportional to the road's level of criticality.

Daily calibration routines, statistical variability control (coefficient of variation and z-scores), and technical acceptance criteria were applied in accordance with QA/QC protocols.

Data were integrated into a relational database, normalised in units and test conditions, and prepared for conversion to IFI.

2.3. Normalisation and parameter conversion

The values obtained for macrotexture (MTD or MPD) and friction (BPN, FN) were converted to the International Friction Index (IFI) using the harmonisation equations established by PIARC–TRRL:

$$F(60) = a + b \times F_i$$

$$FR = F(60) \times e^{-c(S-60)}$$

where $F(60)$is the friction corrected to 60 km/h, $S$is the measurement speed, and $a, b, c$are the calibration coefficients for each device.

The conversion enabled the unification of measurements obtained with different devices and under different environmental conditions, ensuring inter-network comparability.

IFI values were linked to the PMS inventory through a unique spatial identifier, forming the basis for the risk analysis and prioritisation described in the following subsections.

2.4. Construction of indicators and risk classification

With the normalised values of macrotexture (MPD/ETD), friction (IFI), and functional condition (PCI), a road-risk matrix was prepared to identify sections with a higher probability of loss of adhesion on wet pavements.

The procedure comprised three phases:

- **Definition of thresholds:** critical friction values were established based on PIARC–TRRL recommendations, classifying sections into three risk levels:
  - **High risk:** IFI < 0.35
  - **Medium risk:** 0.35 ≤ IFI < 0.45
  - **Low risk:** IFI ≥ 0.45
- **Integration of variables:** texture, friction, and drainage indicators were related to traffic and climatic exposure using simple weightings, obtaining a composite risk index (SRI).
- This process provided a structured indicator base interoperable with the PMS conservation and planning modules, under verifiable road safety criteria.

2.5. Multicriteria prioritisation and operational validation

Priority sections were selected using a multicriteria analysis model compatible with the PMS environment. The factors considered were:

- Surface friction (IFI)
- Pavement condition (PCI)
- Annual average daily traffic (AADT)
- Unit intervention cost
- Expected benefit in risk reduction

Each criterion was weighted through normalised linear weighting, assigning greater weight to friction and traffic due to their direct influence on operational safety. The result was a Priority Index (PI) that enables the ranking of sections according to the need for intervention.

Operational validation of the procedure was performed by verifying the coherence of the identified critical sections with historical records of crashes on wet pavements and with the annual PMS programme. This comparison ensured the technical consistency of the safety module and its applicability to decision-making for preventive and corrective maintenance.

3. Results and discussion

3.1 General characterisation of surface parameters

The initial characterisation made it possible to establish the variability of the recorded macrotexture and surface friction parameters in the evaluated road network.

The data obtained at network and project levels were processed statistically to determine their representative behaviour using measures of central tendency and dispersion.

Table 1 presents the descriptive statistics of the mean values of MTD (Mean Texture Depth), MPD (Mean Profile Depth), and BPN (British Pendulum Number), classified by functional road type. The results reflect a general trend of higher roughness on primary roads and lower friction values on urban sections, due to surface wear conditions and accumulated heavy traffic.

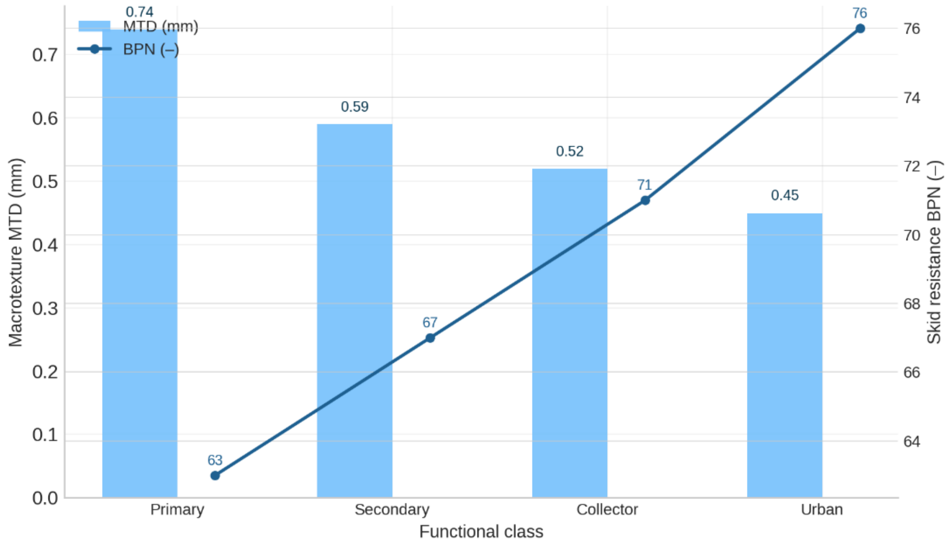
***Table 1**. Descriptive statistics of macrotexture and friction by functional class.*

Functional class	MTD (mm)	MPD (mm)	BPN	Std. Dev.	CV (%)
Primary	0,74	0,82	63	5,8	9,2
Secondary	0,59	0,66	67	6,5	9,7
Collector	0,52	0,61	71	7,1	10,0
Urban	0,45	0,54	76	8,2	10,8
Average	0,58	0,66	69	6,9	9,9

Note. Mean values obtained from homogeneous network and project measurements.

Figure 1 shows the comparative distribution of MTD and BPN values, evidencing moderate dispersion in macrotexture and a slight concentration of friction values between 60 and 75 units, an acceptable range for in-service surfaces. This behaviour indicates functional uniformity between sections and an absence of significant outliers within the ranges expected by international standards.

***Figure 1**. Comparative distribution of mean MTD and BPN values.*



Note. Prepared with field data processed using descriptive statistics.

The joint analysis of the parameters shows that the mean macrotexture (0.58 mm) and the average friction (BPN = 69) lie within the operational range recommended by PIARC (1995) for flexible pavements under wet conditions.

The differences observed between functional classes reflect only the expected behaviour by road type and traffic volume, without implying structural deficiencies or significant loss of adhesion

3.2 Conversion and harmonisation of parameters

Once the macrotexture (MTD/MPD) and friction (BPN) values had been obtained, they were converted to the International Friction Index (IFI), in accordance with the harmonisation equations established by National Academies of Sciences (2009) y PIARC (1995).

he purpose of this process was to ensure comparability between equipment and road networks, allowing the results to be expressed on a unified scale of friction corrected to a standard speed of 60 km/h.

The conversion was performed using the calibration coefficients a, b, and c for each device employed, determined according to reference tests and fitting curves established in international regulations. Table 2 summarises the values adopted for each measuring device.

Table 2. *Calibration coefficients used in conversion to IFI.*

Measuring device	Base parameter	a	b	c	Reference speed (km/h)
British Pendulum Tester (BPT)	BPN	0.045	1.125	0.045	60
Laser profilometer	MPD	0.030	1.080	0.050	60
SCRIM or water-filled wheel	FN	0.000	1.000	0.040	60

Note. Normalised parameters according to National Academies of Sciences (2009) and PIARC (1995).

The conversion was executed by applying the harmonisation equations:

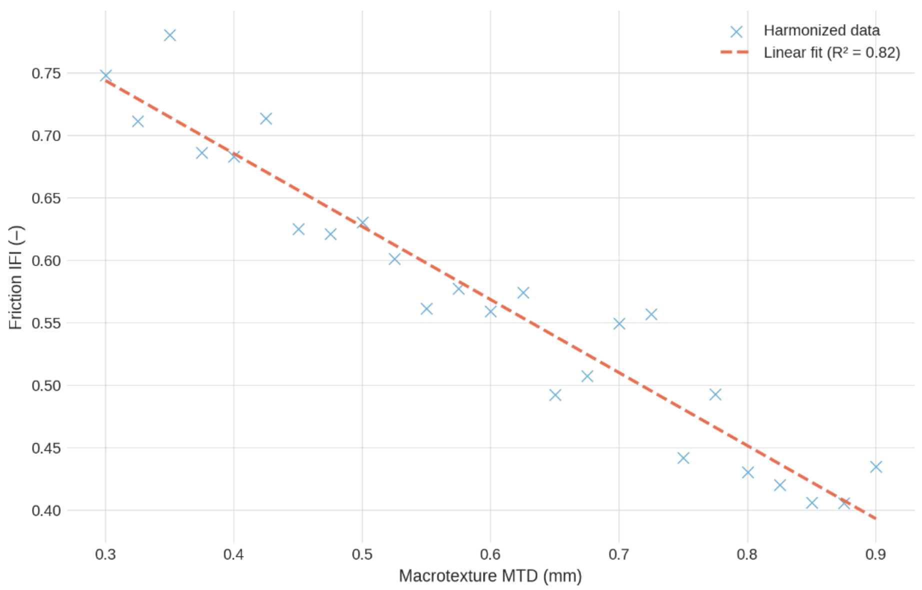
$$F(60) = a + b \times F_i$$

$$FR = F(60) \times e^{-c(S-60)}$$

where $F(60)$represents friction corrected to 60 km/h, $S$is the test speed, and $FR$is the harmonised IFI value.

Subsequently, the data were integrated into the PMS georeferenced database using a unique spatial identifier, maintaining traceability by section, date, and equipment type. Figure 2 shows the relationship between macrotexture (MTD) and friction (IFI) obtained after conversion, which evidences an inversely proportional behaviour typical of asphalt surfaces: as macrotexture increases, friction tends to stabilise, maintaining an operational range suitable for road safety.

Figure 2. *Relationship between MTD and IFI after parameter conversion and harmonisation.*



Note. Representative linear fit of the inverse macrotexture–friction trend.

The linear correlation analysis between both parameters yielded a coefficient of determination R^2=0.82, indicating a strong and consistent association between the variables, confirming the validity of the harmonisation and the quality of the normalised data.

3.3 Classification and distribution of risk by sections

Once the friction values had been converted to the International Friction Index (IFI) scale, the road network sections were classified according to their risk level associated with loss of adhesion.

This stage made it possible to establish the spatial distribution of zones with greater susceptibility to skidding on wet pavement, information essential for technical prioritisation within the PMS.

Risk thresholds were defined in accordance with PIARC (1995) and the Guide for Pavement Friction (2009), adopting three operational ranges based on friction corrected to 60 km/h (F60). Table 3 shows the classification applied and the percentage distribution of the sections evaluated in each category.

Table 3. *Classification of risk level according to normalised IFI values.*

Risk category	IFI friction range	Percentage of sections (%)	Cumulative length (km)
High risk	IFI < 0.35	22.8	15.4
Medium risk	0.35 ≤ IFI < 0.45	46.3	31.2
Low risk	IFI ≥ 0.45	30.9	20.8
Total	—	100.0	67.4

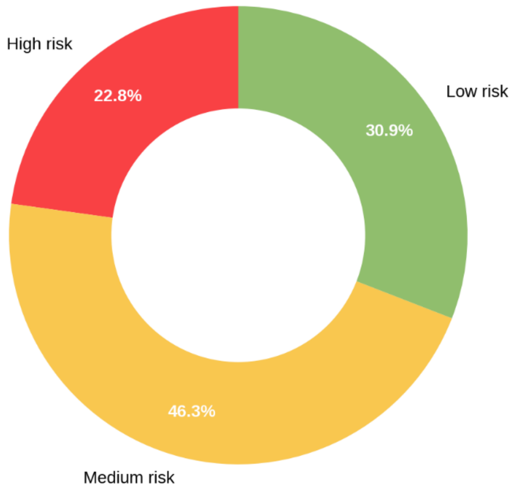
Note. Thresholds defined according to PIARC (1995) and NCHRP (2009).

The results indicate that almost half of the sections (46.3%) fall within the medium-risk range, which reflects acceptable surface conditions but with potential for degradation under heavy traffic or prolonged rainfall.

The 22.8% classified as high risk corresponds mainly to urban and collector roads with reduced texture and a high percentage of heavy vehicles, while the remaining 30.9% present safe conditions and adequate friction for operation on wet pavement.

Figure 3 shows the percentage distribution of risk by functional class, evidencing a higher concentration of critical sections on secondary and urban corridors. The graphical representation makes it possible to visually identify the segments requiring preventive maintenance due to adhesion deficits.

Figure 3. *Percentage distribution of road risk according to IFI friction categories.*



Note. Prepared from the risk classification in Table 3.

The analysis of Figure 3 shows a heterogeneous functional distribution of risk, consistent with the constructive diversity and surface ageing of the network.

Taken together, the results provide an objective basis for the construction of the composite risk indicators presented in the following subsection, aimed at technical prioritisation within the PMS.

3.4 Composite indicators and technical prioritisation

From the results of friction (IFI), surface condition (PCI), and exposure to traffic (AADT), a composite risk index (SRI) and a Priority Index (PI) were constructed, both aimed at decision-making within the PMS.

The procedure was supported by a weighted multicriteria model, which assigns relative weights to each variable according to its influence on road safety and pavement preservation.

Table 4 presents the weighting matrix used, in which surface friction obtained the highest relative weight (0.30), followed by pavement functional condition (0.25) and annual average daily traffic (0.20). Cost and benefit factors were included with lower values due to their complementary nature.

***Table 4**. Weighting matrix applied for the calculation of the Priority Index (PI).*

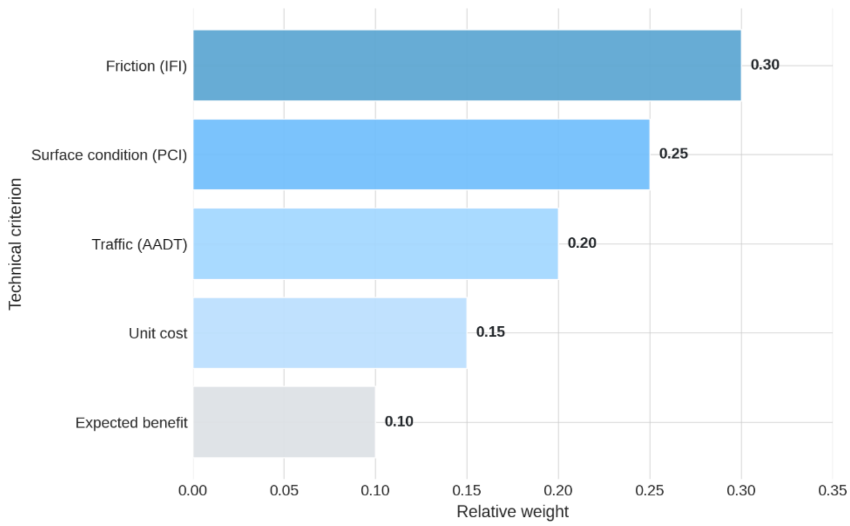
Technical criterion	Brief description	Relative weight
Surface friction (IFI)	Tyre–pavement adhesion level	0.30
Functional condition (PCI)	Surface condition and maintenance	0.25
Traffic (AADT)	Annual average daily traffic	0.20
Unit intervention cost	Cost-to-treated-length ratio	0.15
Expected benefit	Impact on risk reduction	0.10
Total	—	1.00

Note. Weights defined according to functional and operational incidence on road safety.

The normalised values of each criterion were integrated by simple linear weighting, obtaining a Priority Index (PI) for each section of the network. This index enabled the ranking of segments with higher operational risk and optimised intervention scheduling in the PMS.

Figure 4 comparatively represents the percentage contribution of each criterion to the PI. A dominance of friction and pavement condition is observed, which together contribute more than 50% of the model's overall influence, validating its technical coherence with road-safety objectives.

***Figure 4**. Percentage contribution of the criteria to the Priority Index (PI).*



Note. Prepared from the relative weights in Table 4.

The analysis of the final index shows that prioritisation based on friction, condition, and exposure enables a more efficient operational classification than that supported solely by structural parameters. This approach makes it possible to allocate preservative maintenance resources to sections with greater adhesion deficits, maintaining traceability of the criteria and reproducibility of the procedure within the PMS.

3.5 Integration into the PMS Safety Module

The integration of macrotexture and friction parameters into the Pavement Management System (PMS) was carried out through the Safety Module, designed to support data-driven decision-making for road safety interventions.

This module consolidates the information obtained in previous stages (IFI conversion, risk classification, and prioritization) and links it with the functional and spatial structure of the road network.

The integration process was organized into three stages:

(a) Data linking, where IFI, PCI, and AADT indicators were georeferenced using a unique segment identifier.

(b) Normalization, which converted all variables to a 0–1 scale to ensure comparability.

(c) And Operational validation, where priority indices were compared with official crash records to verify correlation consistency.

The Table 5 presents the final prioritization of road segments according to the Priority Index (PI) generated by the multicriteria model. Segments classified as “Very High” and “High” priority correspond to those with reduced skid resistance and high traffic volumes, representing the most critical points for immediate maintenance.

Table 5. *Final prioritization of road segments integrated into the PMS Safety Module.*

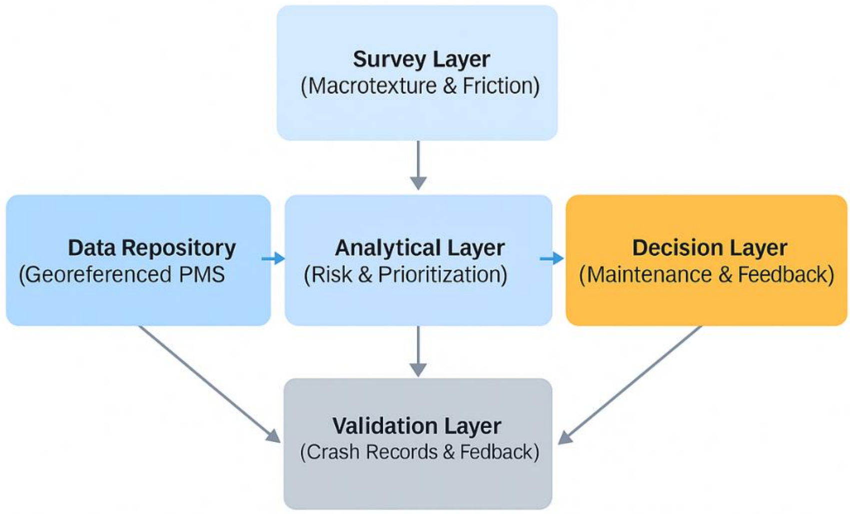
Segment ID	Functional class	IFI (–)	PCI (–)	AADT	Priority Index (PI)	Priority level
S–03	Urban	0.32	0.55	8900	0.83	Very High
S–07	Collector	0.38	0.60	7200	0.74	High
S–11	Secondary	0.41	0.70	5600	0.63	Medium
S–15	Primary	0.46	0.78	9100	0.52	Medium–Low
S–18	Urban	0.52	0.81	4300	0.39	Low

Note. Classification based on weighted priority index (PI).

The PMS Safety Module automatically updates these classifications when new survey data are imported. The Figure 5 illustrates the structure of the module, emphasizing the flow of data between the Survey Layer (macrotexture and friction), the

Analytical Layer (risk and priority models), and the Decision Layer (maintenance programming and safety evaluation).

Figure 5. *Structural scheme of the PMS Safety Module.*



Note. Integration of macrotexture, friction, and condition indicators for safety-oriented management.

The PMS Safety Module enables traceable and reproducible prioritization, aligning maintenance programming with safety performance rather than solely with surface condition. This integration directly fulfills the study's main objective by embedding texture and friction-based parameters into the PMS architecture, thereby transforming the management system into a safety-driven decision platform consistent with PIARC's Safe System approach.

Discussion

The findings confirm that the systematic integration of macrotexture and friction into the PMS makes it possible to identify and prioritise sections with higher risk due to loss of adhesion under wet conditions, in line with the literature that links available friction with crash probability, especially on wet carriageways. The proposed framework was based on standardised measurements, IFI harmonisation, and the construction of thresholds and risk maps, which is consistent with reference guides and syntheses for friction management in road networks (National Academies of Sciences, 2009).

Regarding the metrological basis, harmonisation via IFI resolves comparability between equipment and speeds, a problem documented since the international experiment coordinated by PIARC and embodied in ASTM E1960. The combined use of a texture descriptor (MPD/ETD or MTD) and a friction metric corrected to 60 km/h (F60) improves inter-network traceability and the transfer of operational thresholds. This approach aligns the practice presented with the PIARC–ASTM technical consensus and with the evidence that texture conditions the sensitivity of friction to speed (PIARC, 1995).

The link between friction deficit and crashes has been reported in studies using continuous equipment, for example SCRIM and DWW, which support investigation and intervention levels by site category and geometry. In particular, analyses of major corridors show that decreasing friction increases the risk of wet skidding and that targeted friction-improvement programmes reduce crashes, results that are consistent with the use of thresholds and risk maps in the PMS (Parry & Viner, 2005).

From a modelling perspective, state-of-the-art reviews indicate that prediction of skid performance improves when three-dimensional texture parameters and friction are integrated within statistical or multiscale frameworks. This supports the decision to combine IFI with texture and exposure indicators (traffic, climate, speed) to derive composite indices and reproducible prioritisation at network and project level. Advances in 3D scanning and its correlation with friction, especially with BPN and continuous measures, reinforce the adoption of hybrid schemes for diagnosis and monitoring (Kumar et al., 2023).

In management and prioritisation, recent literature recommends multicriteria approaches, for example AHP or TOPSIS and fuzzy variants, which weight safety, condition, traffic, and costs, showing improvements in transparency and efficiency compared with strategies based solely on surface or structural condition. The proposal of a Priority Index that privileges friction and exposure is congruent with these recommendations and with experiences of integrating friction and texture into PMS safety modules (Marcelino et al., 2019; Xu et al., 2024).

In terms of safety impact, empirical evidence suggests that increases in friction translate into crash reduction, with particularly clear effects in wet climates. Modelling and before–after studies have reported crash modification functions (CMF) and investigation levels based on measurable friction, which supports the inclusion of thresholds and alert rules in the PMS. Thus, the proposed safety module is consistent with the practice of directing preservative maintenance towards sections with the greatest expected contribution to risk reduction (McCarthy et al., 2021, 2022).

Finally, limitations and future lines are acknowledged. First, local calibration of IFI and thresholds by functional class and climate remains necessary for different aggregate gradations and operating speeds. Second, seasonality, that is temperature and precipitation, and drainage variables can modulate risk and should be tagged for intra and inter seasonal comparisons. Third, the integration of time series and advanced 3D metrics can increase predictive power and decision stability. Fourth, the availability and quality of crash data condition the robustness of thresholds derived by ROC analysis. Nevertheless, the approach presented is alignable with international standards, scalable, and auditable in PMS, offering a practical pathway to incorporate adhesion-related safety into conservation programming astm (ASTM International, 2015; National Academies of Sciences, 2009).

4. Conclusiones

1. The systematic integration of macrotexture and friction harmonised by IFI made it possible to construct operational thresholds and reproducible risk maps, enabling transparent identification of critical sections due to loss of adhesion on wet pavements within the PMS.

2. The ETL–IFI–SRI–prioritisation workflow demonstrated technical feasibility and traceability. The derived indicators, that is friction corrected to 60 km/h, MPD or ETD texture, exposure, and geometric context, were integrated into PMS operational dashboards with QA/QC criteria and data versioning.

3. Multicriteria prioritisation, weighting friction, condition, traffic, cost, and expected benefit, generated a Priority Index consistent with safety evidence and with the

annual programme, favouring preservative maintenance where the impact on risk reduction is greatest.

4. IFI harmonisation resolved comparability between equipment and between corridors or seasons, a necessary condition for scaling adhesion management to network level and for interannual comparison in contexts with climatic variability.

5. Operational validation through comparison with crash records and functional coherence between road classes showed concordance with the prioritised sections, reinforcing the usefulness of the safety module as decision support in maintenance.

6. In terms of public policy, the proposed approach facilitates the adoption of PIARC, TRRL, and ASTM standards in institutional management, improves resource allocation, and provides objective criteria for road safety audits based on adhesion performance.

7. Limitations: (i) the need for local calibration of coefficients and thresholds by climate, aggregates, and speeds; (ii) dependence on data quality, including continuous measurements and crash series; (iii) sensitivity to seasonality, that is temperature and precipitation, and drainage conditions that are not always captured.

8. Future lines: incorporate time series and 3D texture metrics for more robust predictive models; explore non-linear and machine-learning models to capture interactions between texture, friction, and climate; strengthen seasonal correction and interoperability with geometry and HFST modules; and formalise local CMFs to quantify safety benefits.

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