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Review

A new methodological approach for road friction deterioration models development based on energetic road traffic characterization

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ABSTRACT

Safety studies have indicated strong correlation between road friction and accident risk, with a dramatic increase in accident when friction drops below certain threshold. For this reason, managing pavement skid resistance is an important mean to reduce crashes. Unfortunately, during the pavement lifespan, skid resistance undergoes to deterioration due to several factors (traffic wear, weathering and aging). The correct management of road pavements implies the knowledge of the performance evolution, obtained both with monitoring and degradation models, however, among those latter available in literature, very few explored the influence of traffic vehicles in terms of type and travel mode. In this paper a new methodology combining the use of road sectioning schemes with a traffic damage criterion based on the dissipated energy at the tire-road pavement contact, for the development of degradation curves from experimental data collected on roads with different traffic, in terms of volumes, vehicle composition and motion conditions, is presented. The methodology has been validated to an open graded bituminous surface course (OGSC) on urban motorway and obtained degradation models have been also compared with those provided by a traditional degradation modelling approach highlighting the superior performance of the proposed approach.

1. Introduction

1.1. Background

Road crashes are considered a public health problem worldwide as more than 1.35 million people die on the world's roads every year according to the World Health Organization [1].

Compared to the global situation, developed countries are doing relatively well, indeed the number of road deaths between 2001 and 2018 decrease by 64 % and 13 % in the EU and USA respectively. However, 25,100 people still lost their lives on EU roads in 2018 (33,000 in the USA roads) and about 135,000 were seriously injured (2.1 million in USA roads). In monetary terms alone, the yearly cost of road crashes in the EU has been estimated in a new study European Road Assessment Programme to be around EUR 280 billion, equivalent to about 2 % of Gross Domestic Product (GDP) .

Several studies have shown that there is a significant correlation between accident risk due to skidding and the pavement's skid resistance in both dry and wet conditions [2,3]; the results of some of these studies are briefly summarized below as examples only. Farber et al. [4] report that only 2.3 % of wet surface accidents occurred on tangent sections of roads, where the friction demand is low. Page and Butas [5] found that accident rates on wet pavement were highest in horizontal curves, especially when side friction coefficient (SFC) was less than 0.25. Viner et al. [6] highlight that amongst the most potentially dangerous driving conditions are those caused by low friction due to heavy rainfall combined with poor road geometry, or those where there is a sudden change in friction, perhaps due to contamination, localized deterioration of the surface or first snowfall. Lyon and Persaud [7], through before-after studies, measured an accident reduction of up to 57 % on road segments and intersections where high proportion of wet-road accidents were identified and low values of friction were tested. In Spain, Mayora and Piña [8] found a 68% reduction of wet-pavement crashes, improving pavement friction from a mean SCRIM value below 50 to a value above 60.

A considerable effect of friction on run-off-the-road crashes was found by many researchers [8,9,10]. A recent study in Italy showed that an increase in grip number (GN) from 0.25 to 0.65 results in a 75 % reduction in wet weather accidents [11].

The above studies indicate that improving and managing road safety

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has a lot to do with friction maintenance and management, which involves a systematic approach intended to measure/monitor friction and accidents, identify needs, and plan/foresee treatments and reconstruction. Selection and prioritization of short and long-term restoration treatments as well as planning and scheduling of friction restoration activities are part of the overall pavement management process [12], for these reasons linking or integrating road safety with pavement management has been the subject of many researches over the past two decades [13–19].

As stated in leading asset management books, `predictions of pavement performance or definition are essential to establish needs' [20], so prediction models for friction deterioration are critical elements for proper action planning and effective integration of safety within Pavements Management Systems (PMSs).

1.2. Objective

In this paper the researches about testing, monitoring and modelling of skid-resistance are briefly reviewed. First, endogenous and exogenous factors affecting skid resistance measures were investigated. Second, friction data analysis and sectioning methods are summarized to evaluate the results of different approaches. Third, skid-resistance degradation models of asphalt pavement are also reviewed, discussing the independent variables considered, with particular regard to the representation of traffic-induced effects and the modelling approaches employed.

The review of the literature has allowed us to highlight some critical aspects in the experimental development of friction degradation models, also highlighting the possibility of using more promising approaches for the analysis and pre-treatment of the measured data, and of improving the development procedures of mechanistic degradation models of pavement friction.

The main goal of this paper is to propose a methodology for the development of a mechanistic road friction deterioration model and to verify its applicability through the analysis of a case study.

The case study analysed consists of an urban motorway with an open course surface layer, which constitutes an additional element of novelty since few deterioration models with such characteristics can be found in the literature.

2. Measurement of skid resistance

2.1. Testing methods

The friction force developed at the contact zone between tire and pavement is called skid resistance [17] and it is influenced by the characteristics of pavement surface, the tire of the vehicle as well as the type of contaminants present on the surface and temperature. From the maintenance management point of view, it is interesting to investigate the contribution to skid resistance related to the key properties of asphalt pavement surfaces. The experimental measurement of this contribution can be carried out through indirect (contactless measurement) or direct measurements. The first one is primarily concerned with measurement on pavement textures [21], such as macro and micro textures, and they are not currently employed because developing realistic models for prediction of pavement friction is very difficult, due to the complicated nature of the tire-pavement interaction.

The traditional approach to friction measurement involves direct measurement of skid resistance by measuring the friction coefficient between tire and pavement by low or high performance measurement devices. Low performance skid resistance devices, like British Pendulum Tester (BPN) and the Dynamic Friction Tester (DFT), are generally used for single-spot or laboratory measurements [22,23].

More than 20 high performance devices are currently in use for field pavement friction monitoring [17], which make use of different testing wheels, different set of slip ratios and/or slip angles and may be operated at different speeds. In particular slip speed is one of the main factors that contribute to the differences between measurements made by different devices [24] and a number of studies have been conducted to harmonize measurements .

The results of these studies have allowed the development of harmonization procedures and the definition of harmonized friction indices: the Skid Resistance Index (SRI) in Europe and, following the PIARC International Experiment, the International Friction Index (IFI) in the USA [25,26].

Although many equipment measurements (including low-performance equipment BPN and DFT) correlate well with each other and with the harmonized indicator some problems still exist for some equipment, e.g. locked wheel skid tester/trailer (LWST) with a ribbed tire [27].

2.2. Measurements variability

The variability of the measurements is due to endogenous and exogenous factors.

Among the most investigated endogenous factors there are certainly accuracy and precision of measuring devices. Accuracy is how close a given set of measurements are to their true value; in order to maintain the accuracy of individual devices under control, calibration requirements are set out in the standards [26]. Precision is measured through the standard deviation (in compliance with ISO 5725 Standards [28]):

$$\sigma_R = \sqrt{\sigma_L^2 + \sigma_r^2}$$

where σ_L is the *reproducibility* i.e. the standard deviation of measurements obtained with the same test method, with different operators using a different device, of the same type, within a short space of time, σ_r is the *repeatability*, i.e. the standard deviation of measurements obtained with the same test method, with the same operators and the same device, within a short space of time.

The precision of existing devices in the European standard is quoted in the Rosanne project [24]. Therefore, accuracy and precision of the equipment are generally under the control and/or in any case known.

In addition to precision and accuracy, there are other factors that can affect friction measurements made with standardized equipment, some of which are related to the measuring equipment and road pavement surface characteristics in the contact area "endogenous factors", others depend on external environmental or site-specific factors "exogenous factors", see Table 1.

In order to limit the variability of skid measures, efforts are made to keep most endogenous factors under control and to mitigate/correct the effects of major exogenous factors.

For example, to minimize the effect of speed, survey requirements usually specify a standard test speed, but as variation in test speed is inevitable during routine surveys (because safety and traffic needs), a speed-correction equation is generally used to convert the measurements into values representative of the standard speed.

However, accurate speed correction requires pavement texture [40] and thus involves the measurement accuracy of this road pavement characteristic (i.e. an error in the macrotexture introduce a bias in the friction measurements).

Similarly, minimization of the effects of vertical load variations are carried out, in recent measuring devices, either by limiting load variability through mechanical devices and directly measuring the load itself and calculating the friction coefficient based on the real load.

As far as exogenous factors are concerned, some can be controlled more easily; for example the effect of temperature on skid measurements, made with different equipment, has been investigated by many researches, which concluded that an adjustment factor can be used to correct the skid number for temperature variations [36,30].

Other factors are more complex to control such as the variability of

Table 1
Factors affecting pavement friction measurements (modified from Mataei et al., 2016) [29], exogenous factor in italic.

Pavement Surface Characteristics	Measurement device factor	Environment	References
• Texture - Microtexture - Macrotexture	• Slip speed - Operating principle - Sleep ratio - Vehicle speed		[30,16]
- Cross section variability	• Lateral position of the device within the lane	• *Traffic type* • *Lane width*	[31,24,16, 30]
• *Unevenness*	• Load	• *Road geometry* - alignment (curvature) - vertical profile	[32,33]
	• Tire - Inflation pressure - Manufacture inconsistency - Storing conditions - Wear of tires	• *Wind*	[24]
• Pavement site meteorological conditions	- Temperature	• *Air temperature*	[34,35,36, 37,30,38]
	• Water flow	• *Contaminants* - Rainfall - Seasonal variation	[39]

friction within wheel paths and the influence of the presence of contaminants in situ.

Although friction measurements should be performed in the centre of the wheel path, variations in the trajectory of the equipment during the measurements are inevitable at speeds of 60 km/h.

Therefore, some measurements (or series of measurements) can be performed in the most lateral parts of the wheel paths and it has been observed changes in grip values of 13 % and 44 % within wheel paths for three-years and 10-years old road pavements, respectively [31].

The effect of contaminants and seasonal variations in friction are interrelated, as matter of fact prolonged periods of dry weather allow the accumulation of contaminants from vehicles, such as oil and grease, and fine particles.

The last one polishes the pavement and, in combination with vehicle contaminates, produces a loss of microtexture and macrotexture and a decrease of friction during the summer months [39]. At the end of this brief examination, it must be concluded that:

- friction measurements carried out continuously on a road can be characterized by a variability due to the precision of the measurement (σ_R from 0,03 to 0,11) to which is added the variability due to other factors;
- measurements made on the same road section at different times, in addition to the factors previously indicated, may show differences due to the state of the surfaces and the presence of contaminants.

2.3. *Friction data analysis*

High performance equipment allows friction measurements to be made with high spatial frequencies (e.g. 1 measurement every 10 m), but the large amount of data collected cannot be used directly given the variability factors previously described.

It is therefore necessary to synthesize and aggregate the data, also because most of the analyses are done using the concept of 'homogeneous sections' where pavements are considered to have uniform/homogeneous friction attributes.

For this reason, approaches to identifying homogeneous data sets and break points between data sets have been the subject of many studies; Table 2 synoptically illustrates the most commonly used methods.

Most of the methods in Table 2 are based on the assumption of independent data. Friction data often show autocorrelation, therefore in such methods data preprocessing/transformation (e.g., Cochrane-Orcutt procedure or geostatistical method) may be required prior to performing data analysis [53].

3. Pavement skid resistance deterioration models: a literature review

A summary of the scientific literature regarding the development of friction degradation models published over the past two decades is presented in Table 3.

The table shows that the most popular approach is regression and that traffic is certainly the most considered factor and the one that has the greatest influence on the evolution of friction degradation. Despite this, most studies do not accurately characterize this action but only consider the traffic volume as independent variable. Recently, some authors have shown that the action of traffic can be characterized more accurately by referring to the energy transmitted in the tire-pavement contact area, which depends not only on the type of vehicle but also on the conditions of motion (e.g. uphill/downhill, cornering, etc.) [54].

Numerous studies also highlight the role of the aggregates quality in the degradation of friction. This aspect implies some critical issues in the development of degradation models. In fact, reconstruction interventions on the surface layer, even on the same road section, can be carried out at different times and/or with materials that are not exactly

Table 2
Approaches used to detect road homogeneous sections.

Method	Criteria	references
Cumulative Difference	Compares the sequence of actual cumulative sums in a measurement series with the sums that would have resulted from adding averages	[41]
Bayesian	Method to detect a change in the mean, in the variance and/or in the autocorrelation of a series using a Bayesian approach that allows communicating the existence and possible location of a change point in terms of probabilities	[42]
Dichotomy "LCPC"	It is assumed that in a homogeneous zone the sequence of values of the measured parameter is distributed according to a Gaussian law, and a dichotomy technique based on the compositional properties of the variance is used.	[43]
Econometrics methods (e.g. ecp, bcp, changepoint, changepoint.np, TSMCP, cpm, EnvCpt, and Wbsts)	Change points detections is based on minimization of a function; many algorithms for finding the minimum have been proposed, the most commonly used ones being: the binary segmentation algorithm [21] the segment neighborhood algorithm [8] and more recently the PELT algorithm [46]. More than 10 R packages are available for the analysis when the number of change points is unknown a priori; most packages detect change points using a threshold on a change-sensitive statistic, including: ecp, bcp, changepoint, changepoint.np, TSMCP, cpm, EnvCpt, and Wbsts	[44–52,]

Table 3
Literature review on friction deterioration models.

Reference	Parameter modelled	Model Type *	Surf. course material**	Independent variables													
				Traffic	Time	Mix volumetric properties	Aggregate properties			Mix mechanical properties		Env. condition		Macro-texture	Micro-texture	Vehicle speed	Road geometry
							Type & Gradation	LA/ MD	PSV	Marshall flow	Marshall stability	rain	Temperature				
Szatkowski, & Hosking, 1972 [55]	MSSC (SCRIM)	RM	–	HCV					PSV								
Wang & Liang, 2014 [56]	SN (LWST)	RM	A	AADT			G		PV								
Cenek et al., 2005 [57]	SFC (SCRIM)	RM	A	HCV					PSV								
Miao et al., 2016 [58]	DFT60 (DF)	RM	A	CTV			T										
Oh et al., 2010 [59]	SN40 (LWST)	RM	OG	ADT	X							X	X				
Rezaei and al., 2013 [60]	IFI (DF)	RM	A	ADT	X		G	MD									
Li et al., 2017 [61]	SN (LWST)	SM	A	AADT	X											X	DC
Marchionna & Paoloni, 1994 [62]	SFC (SUMMS)	F	A,OG	NCV													
Vaiana et al., 2012 [63]	BPN	RM	A		X	X	X										
Omar et al., 2017 [64]	SN (LWST)	RM	A	ESAL		X	X							X			
Santos et al., 2014 [65]	GN (GRIP TEST)	RM	A	AADT									X	X			VA
Fülöp et al., 2000 [66]	IFI (SCRIM)	M	A		X												
Alberti et al. 2017 [67]	SFC (SCRIM)	RM	OG	ESAL	X												
Goulias, & Awoke, 2017 [68]	SN (LWST)	RM	A	AADT			X										
Riemer et al., 2012 [69]	SN (LWST)	RM	A		X												
Cerezo et al., 2012 [70]	SFC (SCRIM)	SM	A	ADT										X			R
Galvis Arce & Zhang, 2021 [71]	SN (LWST)	M	A		X												
Ahammed & Tighe, 2008 [72]	SN (LWST)	RM	C	CVP	X								X	X			
Ahammed & Tighe, 2008 [72]	SN (LWST)	RM	A	CVP	X		X			X	X	X	X				
Wang & Wang, 2013 [73]	FN (LWST)	RM	A	ESAL			X					X	X				
Caliendo et al., 2015 [74]	SFC (SCRIM)	RM	OG	CNT													

(continued on next page)

Table 3 (*continued*)

Reference	Parameter modelled	Model Type *	Surf. course material**	Independent variables													
				Traffic	Time	Mix volumetric properties	Aggregate properties			Mix mechanical properties		Env. condition		Macro-texture	Micro-texture	Vehicle speed	Road geometry
							Type & Gradation	LA/MD	PSV	Marshall flow	Marshall stability	rain	Temperature				
Chowdhury et al., 2017 [75]	SN (LWST) IFI	RM	A	AADT	X	X	G	MD	PV								
Nataadmadja et al., 2015 [76]	μ (WSdevice)	RM	A				T										
Marcelino et al., 2017 [77]	FN	AI	A	ESAL	X							X	X	X			
Pérez-Acebo et al., 2020 [78]	MSSC (SCRIM)	RM	A	AADT					PSVr								NL
Pérez-Acebo et al., 2022 [79]	GRI	RM	A	AADT AADHT													Lane COD
Rith et al., 2020 [80]	SR (ROADSTAR)	RM	EACP	CTV													
Zou et al., 2021 [81]	SFC (SCRIM)	AI	A											X	X		
Odoki & Kerali, 2013 [82]	SFC (SCRIM)	RM	A,OG,	AADHT			X										
Crisman et al., 2019 [83]	BPN	RM	A	EPC	X				PSV								
Llopis-Castelló et.al., 2020 [84]	PCI	RM	A	KESAL								X	X				

Legend: (*) LWST = Locked Wheel Skid Trailer, DF=dynamic friction tester (ASTM International, 2019), GN = Grip number; RM = regression model, SM = Statistical Model, *F* = Fuzzy logic, AI = Artificial intelligence, *M* = Markov Chain Model, *A* = Asphalt mix, OG = Open Graded asphalt, C = Cement concrete, MD = micro Deval, PV = Polishing value, VA = Vertical Alignment, *R* = radius of curvature, DC = degree of curvature, μ = skid resistance values obtained from the Wehner/Schulze device, MSSC = Mean Summer SCRIM Coefficient, SKM= model based on the SCRIM with modifications related to its application in Germany, PCI=Pavement Condition Index, GRI= sideway force coefficient obtained with the SKM (μSKM), NL= number of lanes, PSVr = required Polished Stone Value, EACP = exposed aggregate concrete pavement, HCV = number of heavy commercial vehicle, CVP = cumulative vehicle passes, CNT=cumulative number of truck, CTV = cumulative traffic volume, NCV = number of commercial vehicles/carriageway/day, EPC = equivalent passenger car, AADT = Average Daily Traffic, AADHT= Annual Average Daily Heavy Traffic; ESAL = Equivalent Single Axle Load, KESAL=Equivalent Single Axle Load in thousands, LaneCOD= position of the lane with regard to the total number of lanes.

equal, while still respecting the technical specifications. These differences can produce different evolutions of friction degradation that cannot be identified a priori but which have to be identified through data analysis as will be suggested below. Many of the studies reviewed identify the following two recurring aspects in the evolution of road pavement skid resistance:

1) Immediately after construction, the coefficient of adhesion tends to increase due to the removal of the bituminous binder film coating the surface aggregates, caused by traffic actions (quality control measurements are often performed several months after construction).
2) The skid coefficient in the long term tends asymptotically to a limit value that identifies a sort of balance between the actions exerted by vehicles and the degradation produced.

In addition, it can be observed that very few researches examine open-graded surface course, although they are widely used in developed countries.

Finally, it should be noted that in many experimental studies little attention is paid to the preliminary analysis of data and their aggregation into homogeneous sections.

This aspect is particularly critical in the experimental development of deterioration models both for the variability of data, already highlighted in paragraph 2.2, and because the degradation of initially similar road sections may be different due to the different aggressiveness of traffic (i.e. traction/braking actions, lateral actions in curves, etc.).

4. A general framework for the development of a degradation model

The literature analysis has highlighted some critical issues in the traditional approaches used for the development of friction degradation models. In particular, the use of static analysis sections does not allow taking into account the factors that can influence the evolution of degradation on similar sections (e.g. vehicle motion conditions, small variations in the quality of the materials, etc.) as identification criterion is based only on some initial data (e.g. year of construction, type of material). The studies analysed also highlighted that the factors affecting both the measurements variability and the evolution of friction degradation are not all controllable a priori.

Finally, although the analysis of existing degradation models highlights that traffic is one of the main factors, it has been found that its characterization is roughly carried out. It has been verified that the impact of traffic flows on degradation is traditionally evaluated through the number of vehicle passages, or at most through the number of equivalent vehicle passages but considering fixed equivalence coefficients (see Table 3).

To overcome the previous critical issues, this study proposes an innovative methodological approach to the development of friction degradation models, which is briefly illustrated in the framework of Fig. 1 [85].

To partially resolve the problem of contributory factors that can determine variations both in the measurement and in the evolution of the degradation, the methodology proposes the identification of the analysis sections through the observation and pre-processing of the data themselves with the aid of more sophisticated analysis techniques of spatial series of measurements (see paragraph 2.3). Although spatial series analysis methods should be selected based on the characteristics of the measurement data, carrying out a benchmarking between the results can help in choosing the most reliable method to use for sectioning.

To address the problem of the correct representation of road traffic, the methodology proposes to evaluate the effects of the degradation induced by each vehicle on pavement skid resistance based on the energy dissipated per unit area, taking up studies previously carried out on test tracks [54].

Therefore, using the ratio of dissipated energies, it is possible to homogenize traffic by transforming it into a number of equivalent transit number of a passenger car (EPC), as follows:

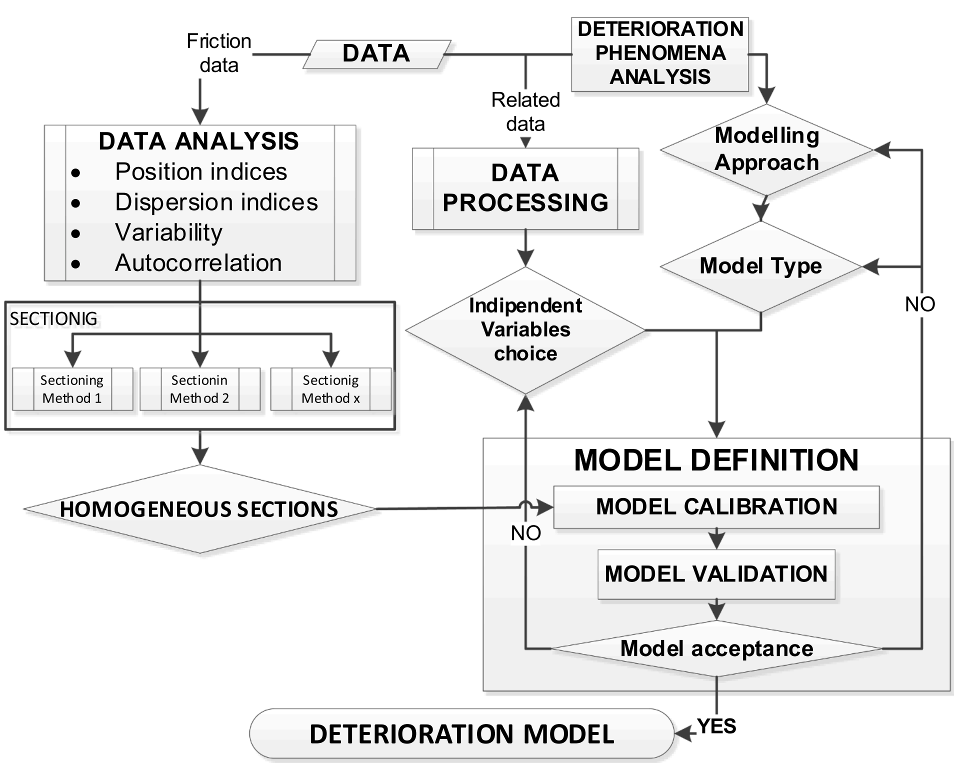


Fig. 1. Framework of degradation models development process (modified from Li 2018) [85].

$$EPC = \sum_{i=1}^{VTN} CT_i \cdot f_i \tag{1}$$

Where:

VTN, is the number of vehicle types detected,

CT_i, is the cumulated number of transits of vehicle type i, f_i is the equivalent degradation factor induced by the vehicle of type i (e.g. truck with mass 10t = 10 equivalent passenger cars) evaluated as follows:

$$f_i = \frac{Dissipated\ energy\ vehicle\ i}{Dissipated\ energy\ passenger\ car} = \frac{k_i \cdot W_i \cdot \sqrt{\frac{W_i}{nw_i \cdot \pi \cdot p_i}}}{k_{pc} \cdot W_{pc} \cdot \sqrt{\frac{W_{pc}}{4 \cdot \pi \cdot p_{pc}}}} \tag{2}$$

k_i and k_{pc} are the average slip coefficients of i-type vehicle and passenger car, respectively [86,87],

W_i and W_{pc} are the total weight of the i-type vehicle and passenger car, respectively [kN], nw_i is the number of wheels in the i-type vehicle, p_i and p_{pc} are the tire pressure of the wheel for the i-type vehicle and passenger car, respectively [MPa].

The relationship between friction coefficient and slip can be considered linear for adhesion values lower than the peak value, or small slip values (i.e. $\mu = k^*s$). This slope k, defined as slip coefficient, is also commonly referred to as the longitudinal stiffness, since it can be justified theoretically from tyre characteristics alone. For this reason, strong differences are found above all between the values relating to commercial and passenger vehicle tyres. Therefore, the values suggested by Bennet for the tires of the latter two categories of vehicles can be used [87], if more accurate data are not available.

It must be underlined that the proposed traffic representation criterion could allow to consider both the different aggressiveness of the vehicles towards the degradation of friction, and the influence of the vehicle motion (e.g. vehicles going uphill, downhill, accelerating or braking).

Finally, it must be highlighted that the proposed methodology is independent of the approach chosen to develop the degradation model (i.e. statistical regression, soft computing or artificial intelligence, etc.), and mainly concerns the preparation and pre-processing of data aimed at developing the models (see also Fig. 1).

As an example, the proposed methodological approach was applied to a real case study for which experimental data were available (see paragraph 5).

5. The case study: a skid resistance deterioration model of a porous asphalt in an urban motorway

5.1. The study site and the available data

The case study analyses an urban motorway in Rome of about 60 km in length, in which there are 20 bridges/viaducts, with a total length of 2.7 km, and 10 tunnels, with a total length of 4.59 km.

Traffic data are collected in 13 sections using 2 technologies: inductive loops and microwave sensors. The average annual daily traffic (AADT) values in one direction varied in the different sections from a maximum of 78,507 veh./day to a minimum of 34,571 veh./day (see e.g. Table 4).

The commercial vehicles were classified into 16 classes (in accordance with the Italian road pavement catalogue) to which were assigned the characteristics reported in Table 5, in order to homogenize the traffic in equivalent cars following the energy criterion introduced in paragraph 4.

The road pavement has a porous asphalt surface layer, whose main characteristics are shown in Table 6. The maintenance actions (surface layer reconstruction) carried out during the time period analyzed are summarized in Table 7.

Friction data have been collected every 10 m through SCRIM equipment ($\sigma_L = 0.06$, $\sigma_r = 0.028 \div 0.035$) in years 2013, 2015, 2016, 2018, and 2019; the dates of measurements are shown in Table 8. The measurements have been carried out at list ten days after last precipitation and after more than a month last resurfacing in order to guarantee the removal of bitumen coating as suggested in literature [92]. The temperature adjustment factor proposed by Transport and Road Research Laboratory (TRRL) has been applied to SFC measurements to take into account temperature effects, and all measurement were referred to the temperature of 20 °C [30].

5.2. Data analysis

A data cleaning procedure has been performed on the data measured in each year in order to detect the presence of missing-data within the series, due to possible operating issues (i.e. operating speed reduction, vehicles traffic stops, etc.) unwanted transients, or spikes. Median filtering is a used to eliminate them replacing these points by the median of those points. The following continuous sequences have been identified: 6 sequences in 2013, 3 sequences in 2015, 2 sequences in 2016 and 2018 and a single sequence in the year 2019.

Individual continuous sequences of measures were examined for the existence of any autocorrelation between measures by both calculating autocorrelation and partial correlation function (Fig. 2) and performing Durbin-Watson and Ljung-Box tests (see Table 9).

From the trend of the correlograms, we see that the series seem to be well represented by a first-order autoregressive model.

In fact, in an autoregressive process of order p the autocorrelation function follows a damped exponential or damped co-sinusoidal trend, while the partial autocorrelation function approaches zero for a lag greater than p.

The tests confirm the hypothesis of a first order autocorrelation between the data, in fact:

Table 4
Traffic volume in one direction (LV = Light vehicles; CV = Commercial vehicles) in the 13 measurement sections.

Year	2014		2015		2016		2017		2018	
Section mileage [km]	LV	CV	LV	CV	LV	CV	LV	CV	LV	CV
7 + 400	45,651	1978	46,227	2040	47,693	2085	48,946	2157	48,570	2210
14+150	48,789	1814	49,584	1835	50,012	1847	50,401	1786	50,990	1927
20+800	33,498	1112	33,984	1029	35,452	1154	36,480	1241	33,469	1102
25+200	58,222	2699	59,338	2779	60,376	2701	65,616	2175	67,651	1964
27+600	52,451	2345	53,955	2412	53,845	2465	54,131	2511	54,809	2773
33+100	63,126	2803	64,254	2899	64,584	2987	64,230	2925	63,555	2885
37+400	70,057	3336	68,540	3369	72,904	3201	73,971	3251	72,602	3229
39+900	68,741	4124	67,988	4175	72,984	4211	74,292	4215	70,109	3823
42+100	57,458	3325	57,696	3455	57,610	3483	60,190	3207	59,508	3411
49+010	54,586	2765	55,410	2714	55,698	2784	62,642	2658	61,039	2744
53+420	53,897	2454	54,511	2502	54,865	2547	57,787	2456	57,430	2544
56+780	62,825	3125	62,021	3127	63,278	3095	63,232	3131	63,472	3199
63+900	50,561	1798	50,874	1769	51,989	1895	52,011	1989	51,835	2177

Table 5
Heavy vehicle classification and damage equivalency factors.

Vehicle type	Vertical axle load [kN]				nw_i	W_i	p_i	k_i	fi
	Axle-1	Axle-2	Axle 3	Axle-4		[KN]	[MPa]		
0) Reference light vehicle	↓6.5	↓6.5			4	13	0,2	0.0285	1
1) Light truck	↓10	↓20			4	30	0,3	0.084	8.4
2) Light truck	↓15	↓30			4	45	0,3	0.084	15.5
3) Medium and heavy truck	↓40	↓80			6	120	0,7	0.084	36.1
4) Medium and heavy truck	↓50	↓110			6	160	0,7	0.084	55.5
5) Heavy truck	↓40	80↓↓80			10	200	0,7	0.084	60.1
6) Heavy truck	↓60	100↓↓100			10	260	0,7	0.084	89.1
7) Articulated truck, truck + trailer	↓40	↓90	↓80	↓80	14	290	0,7	0.084	88.7
8) Articulated truck, truck + trailer	↓60	↓100	↓100	↓100	14	360	0,7	0.084	122.7
9) Articulated truck, truck + trailer	↓40	80↓ ↓80		80↓↓80	18	360	0,7	0.084	108.2
10) Articulated truck, truck + trailer	↓60	90↓ ↓90		100↓↓100	18	440	0,7	0.084	146.2
11) Articulated truck, truck + trailer	↓40	↓100		↓80↓80↓80	18	380	0,7	0.084	117.5
12) Articulated truck, truck + trailer	↓70	↓110		↓90↓90↓90	18	450	0,7	0.084	146.2
13) Earthwork truck	↓40	↓130		↓130↓130↓130	18	560	0,7	0.084	209.9
14) Bus	↓40	↓80			6	120	0,7	0.084	36.1
15) Bus	↓60	↓80			6	140	0,7	0.084	55.5
16) Bus	↓50	↓80			6	130	0,7	0.084	40.7

Note: in vertical axle load one arrow means single axle, two arrows mean double axle, three arrows means triple axle.

Table 6
Main characteristic of the porous asphalt used in the surface course.

Aggregate		Mix properties	
PSV (Polished Stone Value) [88]	≥ 44	Gyratory compactor voids (number of gyrations 50) [89]	≥22 %
Los Angeles test L.A. [40]	<20 %	Indirect tensile strength [91]	360 ÷ 700 [MPa]
Crushed and broken surfaces in coarse aggregate particles [90]	>80 %		

(1) the values of Durbin's statistic are always lower than the dL value with a significance level of 1 % (dL,α=0.01 = 1.664 for lag 1);
(2) the values of Ljung-Box statistic are always more than the chi-square distribution value with degrees of freedom $h = 1$ and a significance level α=0.01.

The identification of autocorrelation in the series data is useful to support the choice of the most suitable sectioning method and to partly explain the different results that the same methods provide

The data were analysed using various sectioning methods (see paragraph 2.3) in order to identify homogeneous sections in the sets of data of each year. The results of these analyses are shown, for the first sequence of year 2015, in Table 10, whose cells indicate the number of breaks common to the sectioning methods shown in the row and column.

Clearly, the diagonal indicates the break points identified by each of the methods examined and the matrix is symmetrical. In order to compare the statistical models generated by the sectioning methods to represent the data, the Watanable-Akaike (WAIC) and Bayesian (BIC) information criteria were used. These criteria, indicated the greater likelihood of the 1st and 2nd order autoregressive models to minimize the relative amount of information lost. Based on this result, also considering the previously acquired indications about a first-order autocorrelation of the data (see e.g. Table 4), the sectioning returned by the EnvCpt R-package with an AR1 model were used in the subsequent analyses (see "EnvCpt AR" method in Table 8 and Fig. 3).

Evaluations performed for the other sets of measurements in other years show similar results, so the results obtained by the "EnvCpt AR" sectioning method were used in subsequent analyses.

Finally, the tunnel sections were removed from the analyses for the definition of the degradation model.

Since for these sections the measured friction values were abnormally lower than for the open-air sections, due to the presence of contaminants that cannot be eliminated in tunnels by rainfall.

5.3. The development of the energy type degradation model

The statistical regression approach was chosen to model the skid coefficient degradation of the case study analysed. Since in the case analysed the surface course material used is practically the same for all sections, it was not possible to consider independent variables related to the characteristics of the porous asphalt.

The only independent variable considered was traffic, and in particular the equivalent number of passenger cars was used, employing the energetic method of vehicle homogenization illustrated in paragraph 4 [54].

Based on the experiences shown in the literature, both in terms of the functional forms employed and the asymptotic tendency toward a boundary value, the following 4 deterioration models were tested:

$$SFC(EPC) = a_1 \cdot \exp\left(\frac{a_2}{EPC}\right) \tag{3}$$

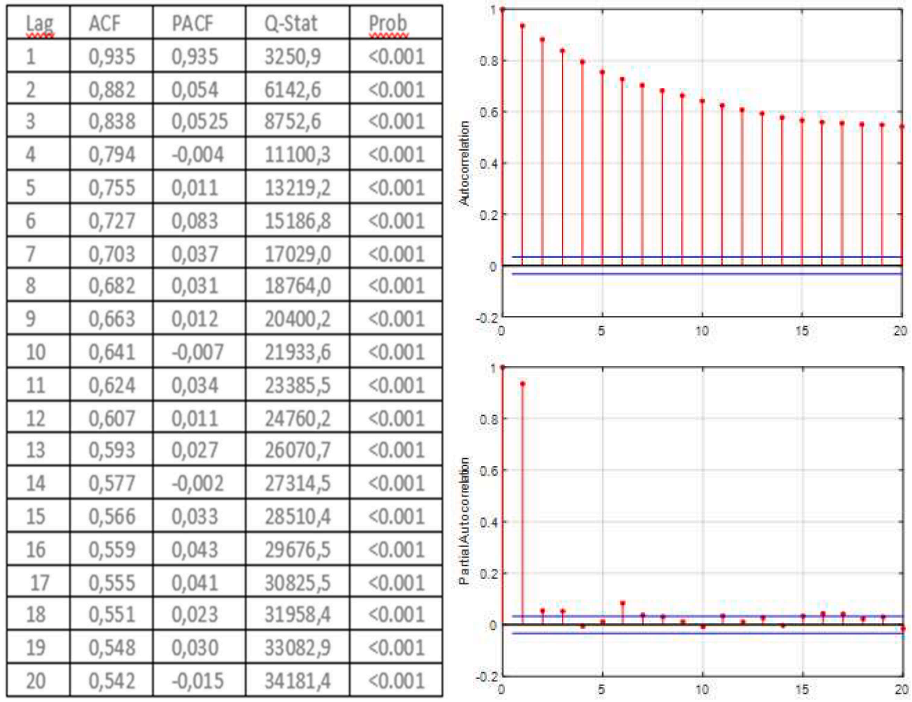
$$SFC(EPC) = a_1 \cdot (EPC)^{a_2} \tag{4}$$

Table 8
Dates of friction measurement campaigns (SFC) using SCRIM equipment.

Year	N. of measurement session	date	Measurement points
2013	6	03/12/2013	6329
2015	3	11/02/2015	6657
2016	2	27/12/2016	6828
2018	2	15/03/2018	6773
2019	1	27/08/2019	6811

Table 7
Length of surface course reconstructed in the year from 2008 to 2019.

Year of maintenance intervention	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Length of maintenance interventions of surface course [m]	5801	11,227	10,393	13,022	2826	28,885	27,715	689	–	6337	–



Lag	ACF	PACF	Q-Stat	Prob
1	0,935	0,935	3250,9	<0.001
2	0,882	0,054	6142,6	<0.001
3	0,838	0,0525	8752,6	<0.001
4	0,794	-0,004	11100,3	<0.001
5	0,755	0,011	13219,2	<0.001
6	0,727	0,083	15186,8	<0.001
7	0,703	0,037	17029,0	<0.001
8	0,682	0,031	18764,0	<0.001
9	0,663	0,012	20400,2	<0.001
10	0,641	-0,007	21933,6	<0.001
11	0,624	0,034	23385,5	<0.001
12	0,607	0,011	24760,2	<0.001
13	0,593	0,027	26070,7	<0.001
14	0,577	-0,002	27314,5	<0.001
15	0,566	0,033	28510,4	<0.001
16	0,559	0,043	29676,5	<0.001
17	0,555	0,041	30825,5	<0.001
18	0,551	0,023	31958,4	<0.001
19	0,548	0,030	33082,9	<0.001
20	0,542	-0,015	34181,4	<0.001

Fig. 2. Autocorrelation and partial correlation functions of the 1st series of data in the year 2015.

Table 9
Autocorrelation tests results.

	Box-Ljung test		Durbin-Watson test	
Series	X-squared	p-value	DW	p-value
2013				
1	656,84	2,20E-16	0.12	2,20E-16
2	261,37	2,20E-16	0.33	2,20E-16
3	100,2	2,20E-16	0.59	2,20E-16
4	456,54	2,20E-16	0.13	2,20E-16
5	45,29	1,70E-11	0.78	1,70E-11
6	4031,7	2,20E-16	0.09	2,20E-16
2015				
1	3250	2,20E-16	0.14	2,20E-16
2	1367,7	2,20E-16	0.16	2,20E-16
3	741,07	2,20E-16	0.29	2,20E-16
2016				
1	2098,5	2,20E-16	0.17	2,20E-16
2	3645	2,20E-16	0.18	2,20E-16
2018				
1	5157	2,20E-16	0.12	2,20E-16
2	689,96	2,20E-16	0.31	2,20E-16
2019				
1	6300,4	2,20E-16	0.09	2,20E-16

Table 10
Sectioning methods results for the first sequence of year 2015 (in the cells are the number of break points common to the methods indicated in the row and column).

SECTIONING METHODS	LCPC	EnvCpt	Changepoint	ecp	EnvCpt AR
LCPC	95	68	51	77	25
EnvCpt	68	114	53	73	38
Changepoint	51	53	62	54	29
ecp	77	73	54	86	25
EnvCpt AR	25	38	29	25	40

$$SFC(EPC) = a_1 \cdot \ln(EPC) + a_2 \tag{5}$$

$$SFC = (a_1 - a_2) + \frac{a_2}{exp(a_3 \cdot EPC)} \tag{6}$$

The results of the statistical regressions performed using the four models are synoptically shown in Table 11, while Fig. 4 shows the normal probability plot of the residuals for model 4 alone as an example.

The model that best represent the experimental data is model 4 (eq. (6)) shown in Fig. 5, which has been previously introduced by D'Apuzzo et al. (2009) [53] and here presented in a form able to favour a physical interpretation of the phenomenon. In fact: the a1 parameter represents the maximum value of the SFC, while the difference (a1-a2) represents the minimum value to which the function tends asymptotically respecting what was found in many experimental studies.

Regardless the specific analytic function that can be employed in order to capture the phenomenological degradation of skid resistance, it can be interesting to compare the obtained model statistics with those provided by a traditional degradation modelling approach that assumes cumulated heavy vehicle traffic as explanatory variable and that does not take into account the spatial variability of the collected data.

In this connection, the same collected data have been analysed by considering only the cumulated wear damage induced by commercial vehicles (regardless traffic composition and vertical forces exerted to the pavement) basing on the historical information on re-surfacing interventions within the examined time span. The same regression models previously employed have therefore been re-calibrated and relevant statistics are conveniently reported in Table 12, while Fig. 4 shows the normal probability plot of the residuals for model 4 alone as an example.

As it can easily be observed by the obtained results, the proportion of variance explained by the explanatory variable dramatically drops to very low values thus confirming the higher prediction performance and the lower uncertainty level provided by the new methodological approach. It is to be highlighted that even errors concerning extreme values of residuals greatly reduce for the proposed modelling approach compared with the traditional one. This implies a higher reliability for modelling framework proposed compared with the traditional one and therefore a more reliable maintenance program can be achieved

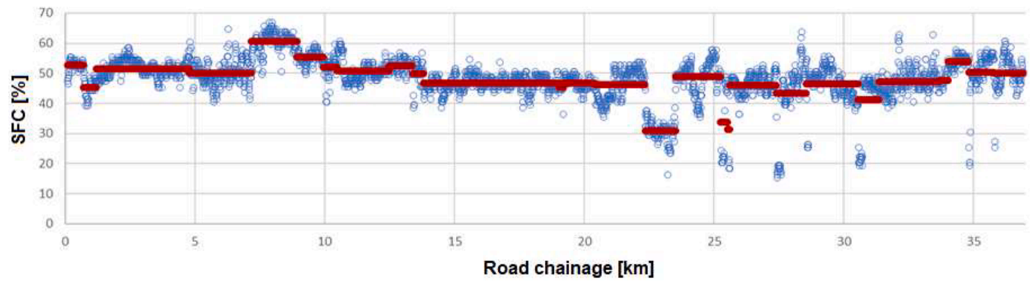


Fig. 3. Homogeneous sections detected by EnvCpt AR method on the first sequence of experimental data of the year 2015.

Table 11
Statistical regression models summary for skid resistance.

Models	Model Summary						Parameter Estimates		
	R	R^2	Adjusted R^2	Std. Error of the Estimate	F	Sig	a_1	a_2	a_3
Model 1 (eq. (3))	0,738	0,545	0,542	3892	190,629	< 0.001	38,468	6147	–
Model 2 (eq. (4))	0,844	0,712	0,710	3097	393,018	< 0.001	92,515	−0,186	–
Model 3 (eq. (5))	0,850	0,722	0,721	3040	413,925	< 0.001	−8448	78,026	–
Model 4 (eq. (6))	0,854	0,729	0,726	3012	212,843	< 0.001	58,336	26,450	0,013

Legend: R is the correlation coefficient between predicted and observed Micro; R^2 is the square of correlation; adjusted R^2 estimates the population R^2 for our model; Std. Error of the Estimate is the standard error of the estimate, also called the root mean square error; F is the Mean Square Regression divided by the Mean Square Residual; Sig is the p-value associated with this F and it is an overall significance test assessing whether the group of independent variables when used together reliably predict the dependent variables (as a rule of thumb, regression is statistically significant if p-value is smaller than 0.05).

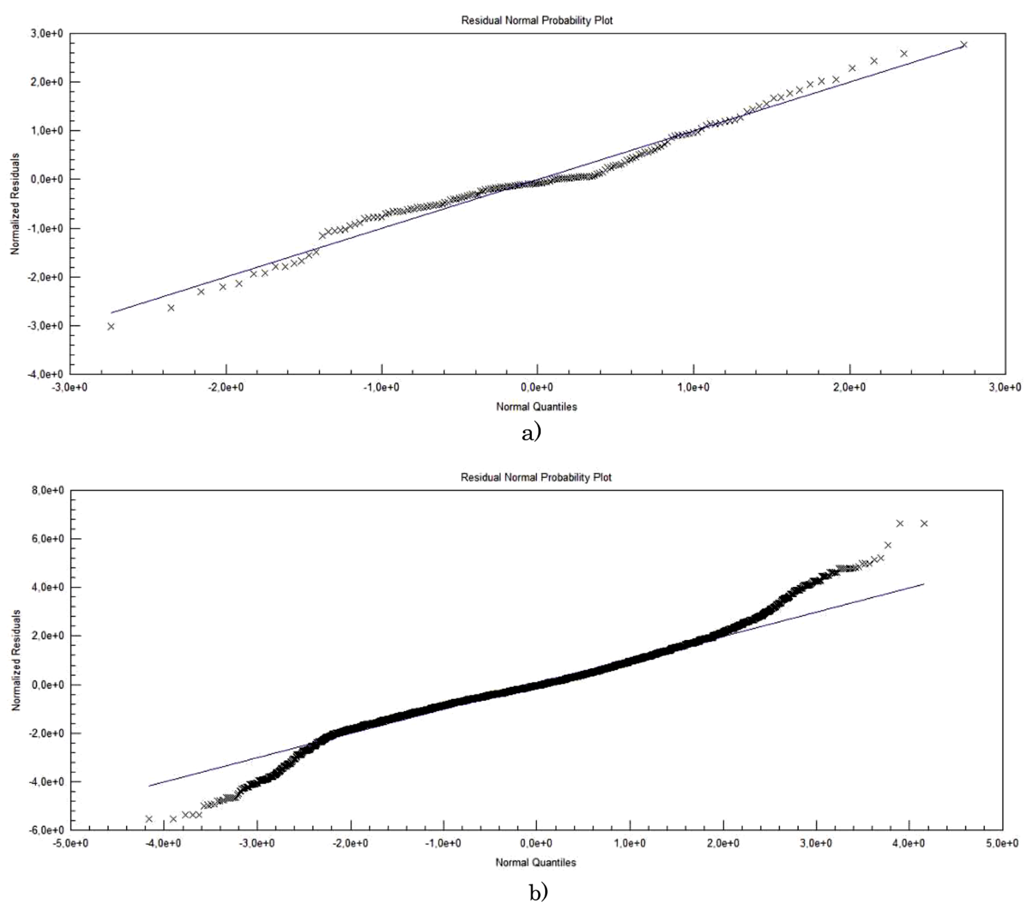


Fig. 4. The normal probability plot of the residuals for the model 4 reported in Table 11(figure a) and the model 4 reported in Table 12 (figure b).

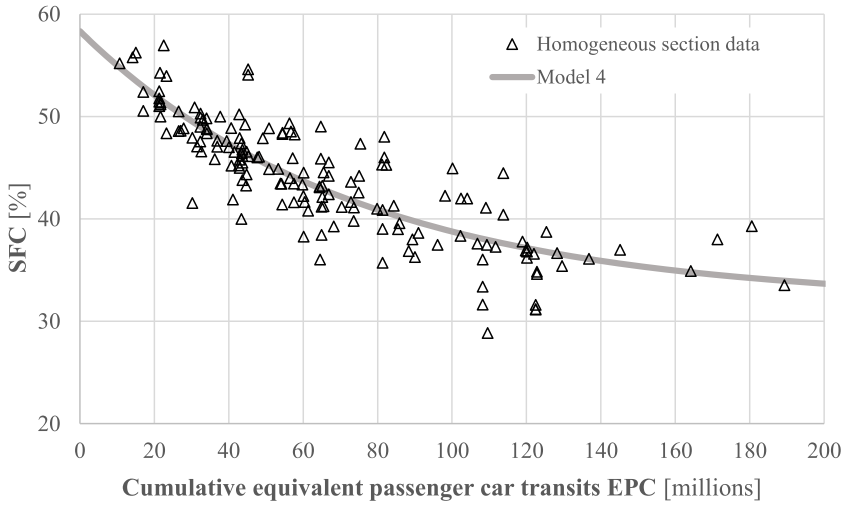


Fig. 5. Side force coefficient deterioration model n.4 (Eq. (6)) and experimental data.

Table 12
Statistical regression models summary for skid resistance by a traditional degradation modelling approach.

Models	Model Summary						Parameter Estimates		
	R	R^2	Adjusted R^2	Std. Error of the Estimate	F	Sig	a_1	a_2	a_3
Model 1 (eq. (3))	0,534	0,285	0,285	6355	12,425,291	< 0.001	38,737	0,192	–
Model 2 (eq. (4))	0,603	0,364	0,364	5997	17,772,478	< 0.001	48,815	−0,175	–
Model 3 (eq. (5))	0,607	0,368	0,368	5975	18,127,083	< 0.001	−7975	48,957	–
Model 4 (eq. (6))	0,608	0,369	0,369	5970	9108,308	< 0.001	57,477	25,034	0,400

following the degradation models developed by the proposed new approach.

6. Conclusion

Prediction of pavement skid resistance degradation with time is of paramount importance as it greatly affects road safety. In this study the problems related to the development of experimental deterioration friction models have been addressed, and, following a wide review of the modelling approaches proposed in the scientific literature, it has been acknowledged the need for an accurate preliminary data analysis to correctly characterize the spatial variability by identifying homogeneous sections.

In addition, a framework for the development of empirical-mechanistic friction models was also developed and a mechanistic approach was identified to evaluate the effects of traffic-induced degradation. The framework was applied to a case study of a long urban motorway, having a porous asphalt surface course. The case study allowed to analyse and compare the various sectioning methods used so far, highlighting which ones seem to be more effective. Within the case study, several degradation models were also compared, showing that the sigmoidal function is better suited to represent the experimental data as well as to represent more clearly the physical friction deterioration phenomenon caused by vehicular traffic. The proposed modelling approach has also been compared with that provided by a traditional degradation modelling where no spatial variability analysis is usually undertaken and damage is only ascribed to cumulated heavy vehicle traffic. The comparison confirmed the significantly higher prediction performance of the proposed approach that, in turn, may provide a more reliable basis for the development of skid resistance driven maintenance programs. However, it has to be also acknowledged that further studies conducted with wear layers made of materials different from the one tested are still necessary to confirm the generality of the preliminary conclusions reached in this study. Furthermore, additional data may be beneficial for the testing/validation of the model. Nevertheless, the proposed methodology seems to be promising in light of a future shift towards a preventive maintenance approach complying with a sounder multi-year allocation budget scenario.

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CRediT authorship contribution statement

Vittorio Nicolosi: Writing – original draft, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Mauro D'Apuzzo:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Azzurra Evangelisti:** Writing – review & editing, Validation, Formal analysis, Data curation. **Maria Augeri:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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