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Deterioration trends of asphalt pavement friction and roughness from medium-term surveys on major Italian roads

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Abstract

Deterioration models are the key factor for effective Pavement Management Systems, helping out road agencies to assess the actual pavement condition and forecast future performance of the asset. Among pavement condition characteristics, friction should be taken into account due to its important effect on user safety, while roughness could be used to express user comfort. The purpose of this study was to provide a reasonable case study for future improvements of Italian road management, even if the length of the analyzed highways was not intended to be representative of the overall Italian network.

This research studied the friction trend (Side Force Coefficient) depending on traffic levels (ESALs) and pavement aging for Italian highways, combining the data with roughness and macrotexture. Surface characteristics were monitored during a seven-year time span. A selection of different road sections with homogeneous traffic levels, similar environmental conditions and surface material was performed and high-speed/high-quality road surveys were used for distress data collection. Pavement deterioration models for Italian road sectors were developed at project level, as starting point to advance pavement management practices in Italy. Degradation curves showed the same trends for similar pavement structures, materials and traffic levels; on the other hand, differences in pavement characteristics, increased ESALs and various maintenance treatments significantly altered those trends.

Keywords: Pavement Management System; Deterioration models; Friction; Roughness; MPD; High-speed monitoring

1. Introduction

The lack of knowledge about condition of the assets does not allow road agencies to clearly identify the required funds for proper maintenance at the required time. As a result, a large amount of money is often wasted on emergency maintenance interventions, which have been proved to be less effective than preventive and corrective maintenance operations. To improve the current practice, a Pavement Management System (PMS) should be developed to address road network critical issues and plan for the best strategies and optimal timing for interventions, relying on updated inventory and database of the actual geometric features, functional and structural conditions of the road network. Due to limited available resources and in the context of global financial crisis, a pavement degradation model could be an essential tool for road authorities and agencies to describe past and present situation of the infrastructure, choose among the best suitable maintenance treatments and support budget allocation scenarios.

Currently, a number of countries already developed degradation models for roads; however, many of them can only be used within the boundary conditions they were developed on and no performance curve can be used for other road networks without proper calibration.

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2. Background and goals

In the available scientific literature, several pavement degradation models can be found, using different approaches and analytical methods: regression equations based on historical field data [1], probabilistic models [2,3], Bayesian statistics with a Markov chains and Monte Carlo simulations [4,5]. Different prediction time spans (forecast horizon) were commonly selected, allowing for short term and long term condition assessment, and several variables were taken into account such as road functional classification, pavement age, traffic loading (ESALs), environmental parameters (temperature and precipitation, for instance), layers thickness, Structural Number (SN); however, an effective and comprehensive model which includes all factors is very difficult to be implemented [6,7]. Moreover, performance assessment and treatment performance models for preventive maintenance on asphalt pavements were studied after several years of monitoring activities. Treatment life and extended pavement service life of thin Hot-Mix Asphalt (HMA) overlays and surface treatments (seal coats, chip seals, etc.) were estimated, according to different pavement condition data (rutting, roughness, macrotexture, etc.) [8–10].

One of the most critical issues regarding Pavement Management Systems is that prediction models do not match actual pavement conditions [11] and, in order to update deterioration curves, pavement performance must be monitored over consecutive years [12,13].

Recently, equipment able to quickly estimate road conditions were developed and high-performance (dynamic) measurements are performed with high-speed vehicles, avoiding traffic interruption or lane closures [14,15]. However, dataset needs to be detailed and reliable because errors can influence maintenance strategies if data collection does not ensure accuracy and precision. For these reasons, analysis techniques based on robust statistics should be performed [16].

Other problems related to road inspections are the lack of knowledge about maintenance history such as treatment applied to pavements without being recorded, the need to remove outliers in the data and pavement sections with unusual performance [13]. To help road managers, software based on Bayesian approach are also adopted to process and automatically analyze pavement data, computing averages, homogeneous section transition and other statistical analyses [17,18].

Several predictive degradation models describe friction behavior of road pavements. Friction data, along with macrotexture, were proved to be effective indicators to monitor pavement conditions [14] and equations were used to describe the degradation trend [19,1].

Roughness is commonly used to determine the comfort of road users running on a road and is useful to provide a general assessment of pavement conditions. Several studies [20–25] dealt with degradation curves of International Roughness Index (IRI) for both new pavements and existing sections [26–28], focusing on the relationships between age, traffic, rut depth, cracking, temperature and type of intervention.

Some studies [29] also proposed linear and exponential IRI performance curves, but these models often included detailed site-specific measurements and, thus, formulas could not be tailored to other local conditions.

In Italy, PMS applications with specific performance curves were developed in the past years [30]; included Side Force Coefficient, IRI and percentage of cracked area into degradation models, although no distress data collection was continuously performed using high-speed/high-quality road surveys.

Data analysis is currently conducted using a clustering approach to identify homogeneous sections and removing all outliers through median, upper and lower quartile calculations.

In this context, the present study shows the results of a seven-year monitoring campaign to evaluate how friction (by means of Side Force Coefficient), International Roughness Index and Mean Profile Depth were influenced by traffic (ESALs) and pavement aging. To this end, two Italian highways were considered by performing a selection of different road sections with homogeneous traffic levels, similar environmental conditions and materials; performance prediction models at project level were finally estimated as described in the following sections.

3. Field survey and research method

Road survey was conducted during spring season from 2008 to 2014; data were collected by adopting high-speed vehicles on two main arterials of the Italian road network in a coastal area (namely, Highway I and Highway II in this paper).

Data monitoring campaigns were carried out annually, from mid-March to mid-May, at least three days after the last rain event. Table 1 shows a range of weather parameters during the analysis period of each year.

Friction, macrotexture and roughness values were collected on the slow traffic lane, along left and right wheel paths; a 10-m spatial frequency was adopted to gather data from a Side Force Coefficient Road Inventory Machine (SCRIM), while a 20-m spatial frequency was used to get International Roughness Index (IRI) values from an Automatic Road Analyzer (ARAN).

The SCRIM measured at the same time both the macrotexture of the pavement, in terms of Mean Profile Depth (MPD, mm) according to ASTM E1845, and the pavement friction Side Force Coefficient (SFC) (ASTM E670) under wet conditions (0.5 mm of water film depth); the ARAN was used to get International Roughness Index (IRI) results according to ASTM E950 and ASTM E1926.

The SFC was computed as follows:

$$\mathrm{SFC}\ (S) = 100 \cdot (FS/W) \tag{1}$$

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Table 1
Ranges of weather parameter values during the analysis period.

Weather parameter	2008	2009	2010	2011	2012	2013	2014
Air temperature (min–max) [°C]	5.9–18.5	7.0–19.0	8.0–17.0	9.0–18.0	9.0–19.0	5.0–20.0	8.0–18.0
Humidity (min–max) [%]	35.0–85.0	31.0–87.0	57.0–92.0	41.0–91.0	47.0–92.0	61.0–91.0	51.0–91.0

where: S is the actual slip speed of the equipment (60 km/h in the study); FS is the force perpendicular to the plane of rotation [N]; W is the vertical load applied to the tire [N].

SFC(S) data were then corrected according to ASTM E1960 to take into account the vehicle speed variations during the data collection and effect of pavements' macrotexture. Thus, the $FR(60)$ value, which represents the adjusted value of friction SFC(S) at a slip speed of S to a slip speed of 60 km/h, was obtained by the following formula:

$$FR(60) = \mathrm{SFC}\ (S) \cdot \exp((S - 60)/(14.2 + 89.7 \cdot \mathrm{MPD})) \tag{2}$$

Then, another formula [31] was used to eliminate the effects of different pavement surface temperatures (t is the recording temperature, °C) during data collection in the field:

$$\mathrm{SFC}(60\ \mathrm{km/h}, 20^{\circ}\mathrm{C}) = FR(60)/(0.548 + 44.69/(t + 80)) \tag{3}$$

The experimental program was divided into different steps.

The first phase included the identification of homogenous road sectors in terms of traffic levels (Annual Average Daily Traffic – AADT), pavement structure, materials and driving directions.

Traffic was divided into five classes according to common distribution on Italian highways: passenger cars and motorcycles, 2-axle light trucks including buses, 3-axle medium trucks, 4-axle heavy trucks and 5 or more axles heavy trucks. Four macro-sectors with homogeneous traffic levels were identified: Macro-sector A and Macro-sector B on Highway I, Macro-sector C and Macro-sector D on Highway II.

As shown in Table 2, traffic data were converted into ESALs (Equivalent Single Axle Loads) and then into Cumulative ESALs (CESALs) to relate damage assessment to pavement age and traffic loading. Structural Number (SN) of 12 cm and minimum Present Serviceability Index (PSI_f) equal to 2.5 were assumed in ESAL computation, according to pavement materials.

Highway pavements were made by 26 cm of asphalt concrete (5 cm open-graded friction course – 22–26% of air voids, 9 cm intermediate layer, 12 cm base layer, evaluated using a Ground Penetrating Radar) over 20 cm of unbound granular material as foundation layer, and compacted subgrade. The analyzed roads were built according to the common Italian pavement structure on highways and, therefore, even if the total length of analysis is not representative for the overall national network, they could still provide a reasonable figure for future studies.

The second step was to identify homogeneous sections within the macro-sectors in terms of collected friction data (Side Force Coefficient). Adjustments were conducted due to odometer shifts that caused offsets of the data reference point from year to year. A segmentation process based on clustering analysis [32] was performed, using differences in moving average to evaluate the initial/final limit of the homogeneous sections.

Upper and lower quartiles were computed in order to remove all outliers, which could potentially affect the analysis.

Right and left Side Force Coefficient – SFC (60 km/h, 20 °C) were very similar, the mean SFC (60 km/h, 20 °C) value was therefore considered for a specific year in this study.

Fig. 1 shows an example of segmentation process for one of the macro-sectors (i.e., Macro-sector A).

Four homogeneous sections (one for each macro-sector in Table 2) with lane width of 3.75 m were identified by analyzing mean values and standard deviation of clusters. For Sections 1, 2 and 4 the last resurfacing intervention was recorded in 2007; Section 3 instead presented a surface

Table 2
Highway macro-sectors and ESAL computation.

Annual ESALs	2008	2009	2010	2011	2012	2013
Macro-sector A	3,881,962	3,719,686	3,573,554	3,452,956	3,143,940	3,002,537
Macro-sector B	3,726,434	3,576,381	3,453,639	3,327,226	3,027,865	2,924,938
Macro-sector C	3,999,439	3,818,719	3,662,180	3,486,038	3,186,837	3,063,691
Macro-sector D	5,135,517	4,929,209	4,740,794	4,599,951	4,202,535	4,044,180
CESALs	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Macro-sector A	3,881,962	7,601,647	11,175,201	14,628,157	17,772,097	20,774,634
Macro-sector B	3,726,434	7,302,815	10,756,454	14,083,680	17,111,545	20,036,482
Macro-sector C	3,999,439	7,818,158	11,480,338	14,966,377	18,153,213	21,216,905
Macro-sector D	5,135,517	10,064,726	14,805,520	19,405,471	23,608,006	27,652,186

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maintenance treatment (mill & fill) in 2009, before the field survey.

An example of homogeneous cluster connection is reported in Fig. 2 (i.e., Section 4 – 650 m in length).

In the third phase, a degradation model was developed by taking into account Side Force Coefficient, pavement age and Cumulative ESALs.

Finally, the same procedure was applied to Mean Profile Depth (MPD, mm) and International Roughness Index (IRI) data; this entailed identifying homogeneous sections within the macro-sectors, performing a segmentation process and removing the outliers, in order to better understand the pavement behavior of the analyzed road sectors at project level.

4. Results and discussion

Tables 4 and 6 summarize statistical values (mean and standard deviation) of the sections identified in Table 3 (SFC) and in Table 5 (MPD). Fig. 3 shows SFC (60 km/h, 20 °C) and MPD [mm] trends during the seven-year monitoring campaign, without including the outliers.

In Fig. 3, both median (bold line), upper (Q3) and lower (Q1) quartiles and the range of acceptability ±1.5·

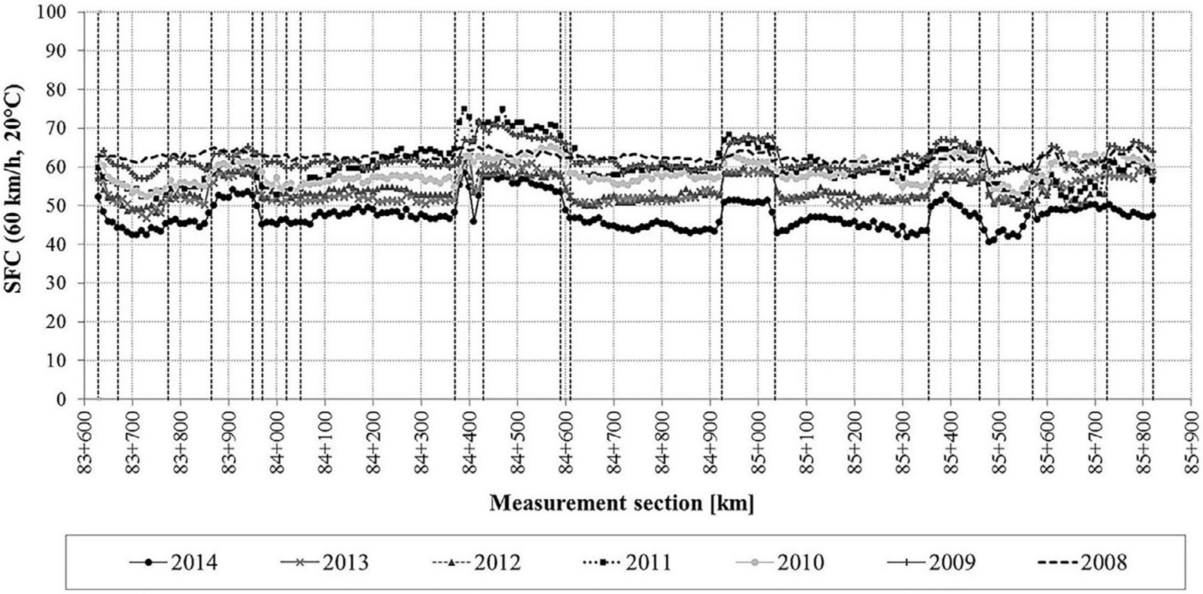

Fig. 1. Segmentation process for the identification of homogeneous sections – Macro-sector A.

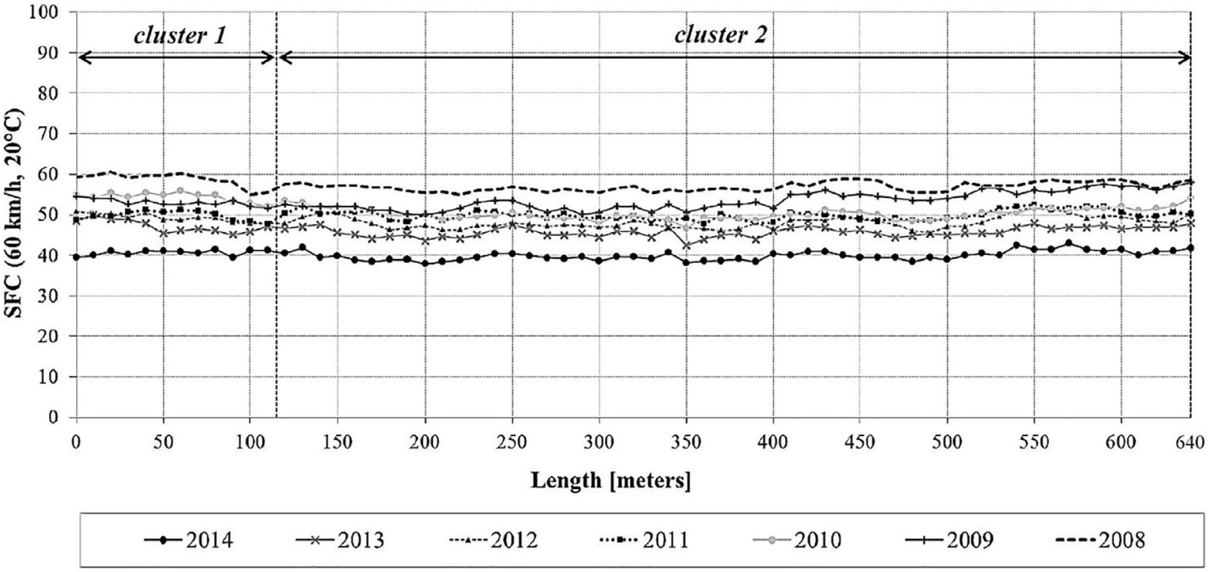

Fig. 2. SFC trend over seven years of analysis – Highway II, Section 4.

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Table 3
Section characteristics – SFC (60 km/h, 20 °C).

Macro-sector ID	Highway ID	Direction	Section ID	Length [m]	Model ID
Macro-sector A	Highway I	East–West	Section 1	1120	A.1.EW
Macro-sector B	Highway I	West–East	Section 2a	300	B.2a.WE
			Section 2b	840	–
Macro-sector C	Highway II	South–North	Section 3a	760	C.3a.SN
			Section 3b	1010	C.3b.SN
			Section 3c	2,490	C.3c.SN
Macro-sector D	Highway II	North–South	Section 4	650	D.4.NS

(Q3 – Q1) are given. Because various factors affected data distribution (including lateral displacements of the survey vehicle, equipment deficiency, specific environmental conditions or presence of work sites) 4.2% of friction values of Section 1 were not considered in the analysis; 2.4% of Section 3a and 3.0% of Section 3b were excluded as well.

According to Table 4, Section 2a presented the greatest data variability, especially for 2008 and 2009; this was probably due to the short length of this section. In addition, data of Section 1, Section 3b and Section 4 overall presented a small difference between upper and lower quartiles (Fig. 3), highlighting a high data homogeneity within the same monitoring year.

As for SFC, different percentages of macrotexture values were excluded from the analysis for the same reasons; 1.8% of Section 1, 2.4% of Section 2a′, 2.9% of Section 2b, 2.9% of Section 3a, 3.9% of Section 3b, 2.1% of Section 3c′, 3.5% of Section 3c″ and 3.5% of Section 4.

According to Table 6, Sections 2a″ and 2b presented the greatest data variability, especially for 2011; this was probably due to specific MPD conditions during that year, as macrotexture showed high values and maintenance was also performed (Fig. 3 shows a decrease in MPD and lower data variability can be seen in 2012–2014). Section 1, Sections 3 and Section 4 presented a small difference between upper and lower quartiles (Fig. 3), highlighting a high data homogeneity within the same monitoring years.

Graphs in Fig. 3 show a general decrease of SFC (60 km/h, 20 °C) over time, providing evidence of the aging deterioration processes which affected road pavement. However, Sections 3a, 3c and, especially, Section 3b showed a very low SFC value at the initial year of measurement (2008) if compared to the following year (2009); Section 3b SFC value was even below the threshold level established by the highway agency (corresponding to a high value of macrotexture and thus emphasizing consistency between indicators). Based on available maintenance information, it can be inferred that a surface treatment was performed between 2008 and 2009.

By analyzing Sections 1 and 2a, average SFC values deviating from the decreasing trend can be spotted for 2011. According to the records, no maintenance activity was conducted during 2010–2011, but treatments applied to pavements cannot be excluded. An unrecorded maintenance intervention seemed to have happened before the monitoring campaign on Section 1, while was supposed to be performed after the inspection activity on Section 2a.

Sections 2b showed an initial physiological decrease of friction, followed by a small increase in 2011, probably due to a degradation of the wearing course (Fig. 3 shows a very high MPD value); maintenance activity can be spotted before the 2012 survey was taken and friction and macrotexture values were raised up to 71.0 and 1.17 mm, respectively.

Fig. 4 shows the degradation rate compared to the first monitoring year for the four sections. Sections 3a–3c were compared to 2009 due to the maintenance activity carried out before the survey.

Section 1 and section 2a exhibited a smaller SFC degradation percentage in 2011 and 2012. This could be explained by maintenance works, which were conducted but not recorded, as mentioned above. Section 2b was characterized by an unusual trend, due to the degradation process over time and the performed intervention. Section 3 presented a steep SFC reduction between the first two years, followed by a flat trend and a clear change in the last two years of monitoring. Sections 3a and 3c showed the greatest degradation rate, while Section 4 provided a very constant value of SFC loss over the years.

MPD values were characterized by an initial decrease over time, followed by a small increase over the next years, a plateau value of about 1.25 mm in the seventh year of monitoring (except for Section 3a with a slightly higher end value of 1.50 mm) and a gradual final rise. The initial decrease suggests the removal of the binder film from the aggregate surface due to traffic that leads to a partial clogging of the intra-aggregate pores; then the removed asphalt binder in open-graded wearing courses leads to a small increase in macrotexture. The MPD increase in the final-stage, instead, shows progressive raveling of the wearing course due to traffic cycles with the finer particles losing the bond with the road surface.

The analyzed sections showed the same macrotexture trend over time, but Sections 2a′, 2a″ and 2b presented a poor macrotexture due to various distresses, basically raveling and potholes on the surface, which led to maintenance interventions after the 2011 survey was taken; simple patching was, in fact, conducted on Sections 2a″ and 2b.

Degradation models could thus provide useful information at project level to plan proper maintenance and identify road sectors in needs of an immediate action.

In Fig. 5, the SFC (60 km/h, 20 °C) is plotted as a function of time (year ‘zero’ is the first year of the survey or the

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first year after a mill & fill maintenance treatment). The graphs in Fig. 5(a) and (b) are related to Highway I (no models were developed for Section 2b due to pavement surface degradation) and Fig. 5(c)–(f) refer to Highway II. The degradation curves revealed that friction loss over time can be described by a third-degree polynomial function with great accuracy. SFC equation and 95% confidence interval are reported.

It can be inferred that a maintenance action was performed on Sections 3a, 3b and 3c in 2009, displaying Sections 3a and 3b with the same initial SFC value, but Section 3a decreased faster than Section 3b and it showed worse distress conditions after five years. Friction on Section 4 was smaller at the beginning, but slowly decreased over time and the model also fitted very well.

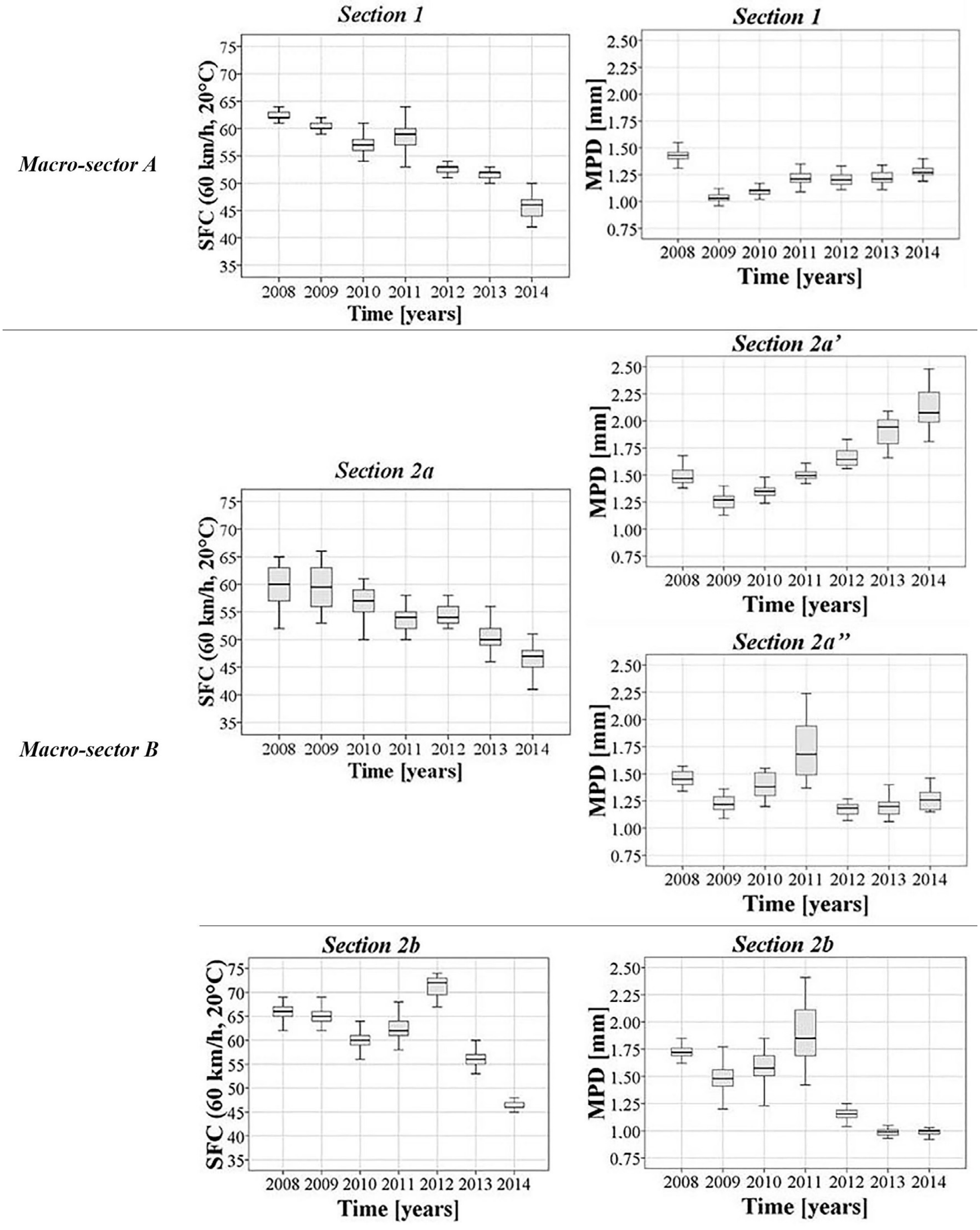

Fig. 3. Boxplots of collected data – SFC (60 km/h, 20 °C) and MPD [mm].

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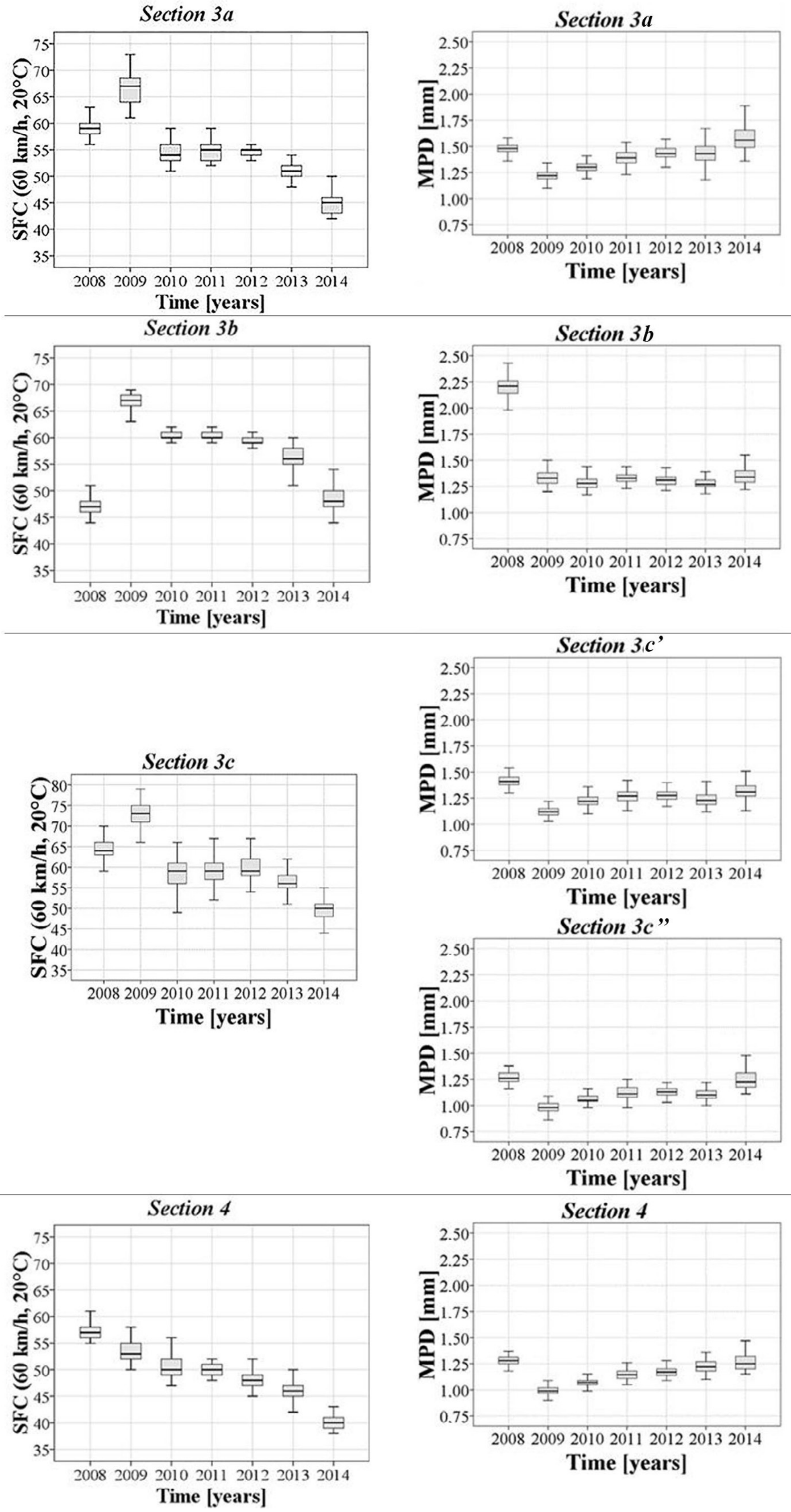
Section 3a

Section 3a

Section 3b

Section 3b

Section 3c

Section 3c'

Section 3c"

Section 4

Section 4

Macro-sector C

Macro-sector D

Fig 3. *(continued)*

Table 4
Statistical values of recorded data – SFC (60 km/h, 20 °C).

SFC (60 km/h, 20 °C) statistics	2008	2009	2010	2011	2012	2013	2014
Section 1							
Mean	62.3	60.6	57.0	59.0	52.6	51.6	45.8
Standard deviation	0.73	0.91	1.40	2.56	0.93	0.73	1.73
Section 2a							
Mean	60.1	59.3	56.7	53.8	54.4	50.5	46.6
Standard deviation	3.51	3.66	2.89	2.23	1.64	2.46	2.52
Section 2b							
Mean	65.8	64.8	60.1	62.5	71.0	56.0	46.6
Standard deviation	1.56	1.63	1.65	2.14	1.85	1.86	0.92
Section 3a							
Mean	59.3	66.3	54.6	54.6	54.5	51.2	44.9
Standard deviation	1.41	2.88	1.77	1.51	1.02	1.31	1.65
Section 3b							
Mean	47.4	67.1	60.3	60.1	59.4	56.1	48.6
Standard deviation	1.40	1.37	0.71	0.80	0.80	2.03	1.84
Section 3c							
Mean	64.7	73.1	58.5	58.9	59.7	56.3	49.6
Standard deviation	2.44	2.89	3.47	2.88	2.63	2.31	2.42
Section 4							
Mean	57.2	53.4	51.0	49.8	48.3	46.0	40.0
Standard deviation	1.43	2.10	2.13	1.18	1.48	1.41	1.13

Table 5
Section characteristics – MPD [mm].

Macro-sector ID	Highway ID	Direction	Section ID	Length [m]
Macro-sector A	Highway I	East–West	Section 1	740
Macro-sector B	Highway I	West–East	Section 2a′	240
			Section 2a″	180
			Section 2b	310
Macro-sector C	Highway II	South–North	Section 3a	1380
			Section 3b	950
			Section 3c′	1860
			Section 3c″	580
Macro-sector D	Highway II	North–South	Section 4	880

It should be further pointed out that the initial slope of the curve was not identified for Sections 1, 2 and 4; this was probably due to maintenance interventions conducted in 2007 instead of 2008 as for Section 3.

Some comments can be done if comparing friction to macrotexture values on each road section previously analyzed. Highway I East–West direction (Macro-sector A) showed a corrective structural intervention before the 2011 monitoring campaign, without significant effects on macrotexture and very small impact on friction.

SFC degradation curve of Highway I West-East direction (Macro-sector B) highlighted a maintenance action after the 2011 survey, while MPD homogeneous sections presented different behaviors; Section 2a′ displayed a progressive increase in macrotexture, pointing out distresses such as raveling or extension of potholes, Sections 2a″ and 2b were characterized by a steep increase in macrotexture during the first four years, followed by localized maintenance interventions that were able to reduce MPD values below 1.25 mm (according to SFC trends).

On Highway II South-North direction (Macro-sector C) all the analyzed sections showed a 2008–2009 maintenance action in SFC trends, while no similar activity can be found in MPD curves showing an initial decrease followed by a rapid raise and a sort of equilibrium over time.

Highway II North–South direction (Macro-sector D) showed degradation curves with no maintenance interventions during the seven years of monitoring (the last recorded maintenance intervention was conducted in 2007, before the surveys took place).

Fig. 6 shows SFC (60 km/h, 20 °C) over CESALs. Highway I presented the same trend for both driving directions (Fig. 6(a)), due to the equivalent traffic level of Macro-sector A and Macro-sector B; SFC exhibited 25% decrease after 20 million ESALs. On the other hand, Highway II showed different trends on the two driving directions (Fig. 6(b)), because of variations in the traffic flows on Macro-sector C and Macro-sector D. Highway II North–South direction (Macro-sector D) withstood more traffic than Highway II South-North direction (Macro-sector C), but degradation occurred more slowly. This assumption can be verified using a data extrapolation: Highway II North–South direction reaches the SFC threshold (value of 40) at 27.5 million ESALs, Highway II South-North

Table 6
Statistical values of recorded data – MPD [mm].

MPD [mm] Statistics	2008	2009	2010	2011	2012	2013	2014
Section 1							
Mean	1.43	1.03	1.09	1.22	1.20	1.22	1.28
Standard deviation	0.05	0.04	0.03	0.06	0.06	0.06	0.05
Section 2a′							
Mean	1.49	1.25	1.35	1.50	1.66	1.90	2.11
Standard deviation	0.08	0.07	0.06	0.05	0.09	0.12	0.17
Section 2a″							
Mean	1.46	1.22	1.39	1.72	1.17	1.19	1.26
Standard deviation	0.07	0.08	0.11	0.25	0.06	0.09	0.09
Section 2b							
Mean	1.71	1.48	1.58	1.85	1.14	0.99	0.98
Standard deviation	0.05	0.13	0.12	0.22	0.05	0.04	0.03
Section 3a							
Mean	1.48	1.22	1.30	1.39	1.43	1.44	1.58
Standard deviation	0.04	0.05	0.04	0.07	0.06	0.10	0.12
Section 3b							
Mean	2.21	1.33	1.28	1.33	1.31	1.28	1.35
Standard deviation	0.10	0.07	0.06	0.05	0.05	0.05	0.08
Section 3c′							
Mean	1.41	1.12	1.22	1.27	1.27	1.24	1.32
Standard deviation	0.05	0.04	0.05	0.06	0.05	0.06	0.08
Section 3c″							
Mean	1.27	0.98	1.06	1.12	1.13	1.11	1.24
Standard deviation	0.05	0.05	0.04	0.06	0.04	0.05	0.09
Section 4							
Mean	1.27	0.99	1.07	1.15	1.17	1.23	1.26
Standard deviation	0.04	0.04	0.03	0.05	0.05	0.06	0.08

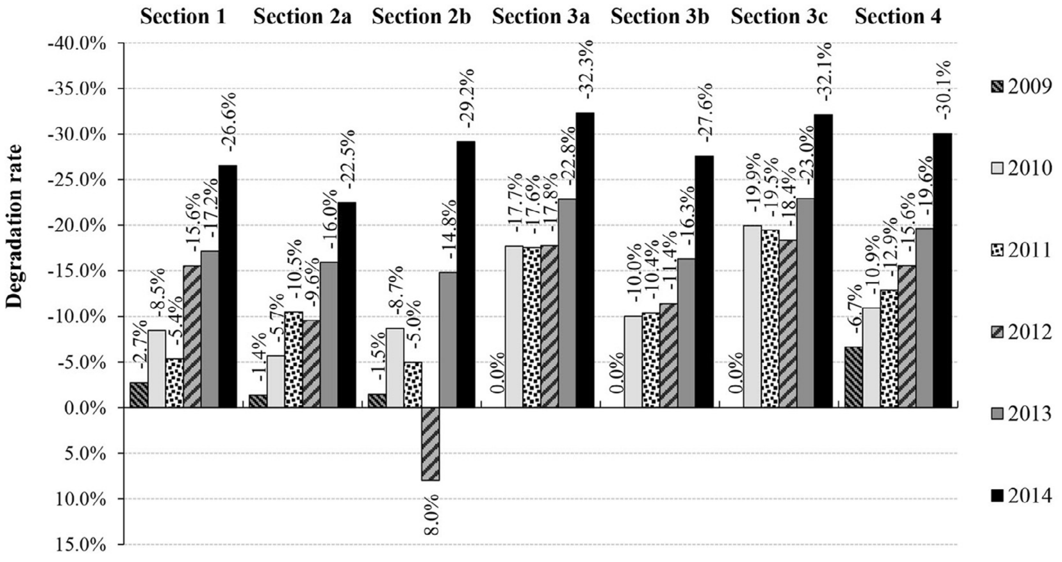

Fig. 4. Friction loss compared to 2008 value (2009 for Sections 3).

direction instead achieves the same value after 17.5 million ESALs and Highway I provides an intermediate response with 22.5 million ESALs to get to the same condition.

Fig. 6 shows the same trend for Highway I East–West direction and Highway I West-East direction, under equal pavement structure, material, initial SFC (60 km/h, 20 °C) value and traffic level. Highway II North–South direction had about 1 million of annual ESALs more than Highway II South-North direction (a difference in traffic level of about 30%) and was characterized by an initial SFC (60 km/h, 20 °C) lower than 10%. However, Highway II North–South direction showed a Side Force Coefficient 25% higher than II South-North direction after 17.5 millions of ESALs.

To compare different surface characteristics of the road pavements the analysis also included roughness data by means of International Roughness Index – IRI [m/km], which was recorded on the same macro-sectors and during

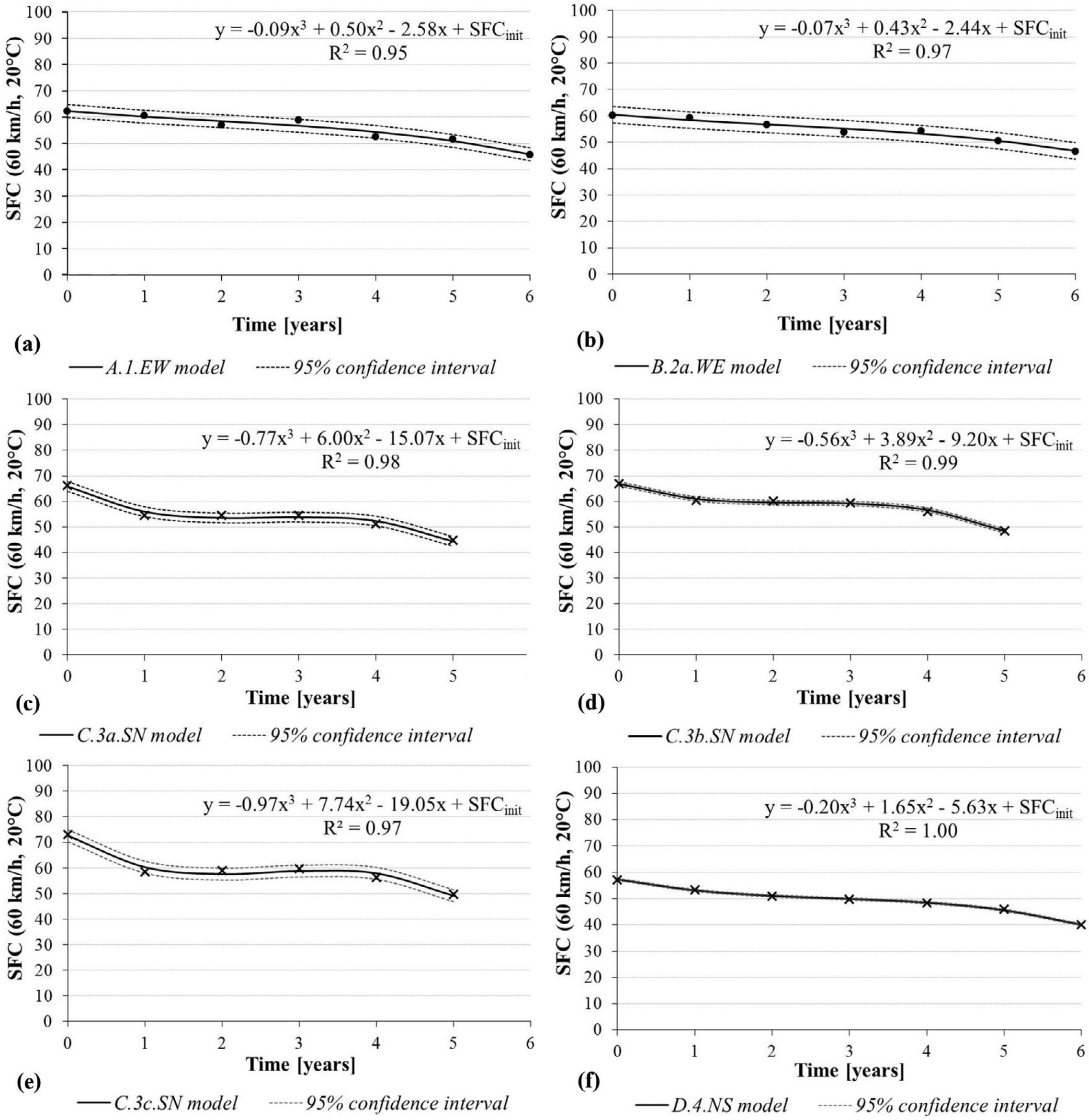

Fig. 5. SFC (60 km/h, 20 °C) degradation models.

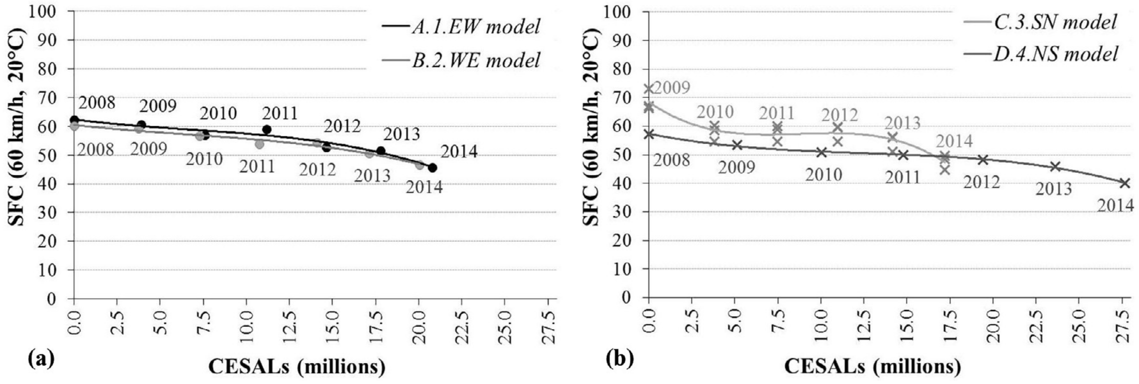

Fig. 6. Side Force Coefficient versus Cumulative ESALs.

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Table 7
Section characteristics – IRI [m/km].

Macro-sector ID	Highway ID	Direction	Section ID	Length [m]	Model ID
Macro-sector A	Highway I	East–West	Section 1	2700	A.1.EW
Macro-sector B	Highway I	West–East	Section 2	5240	B.2.WE
Macro-sector C	Highway II	South–North	Section 3	8040	C.3.SN
Macro-sector D	Highway II	North–South	Section 4	3720	D.4.NS

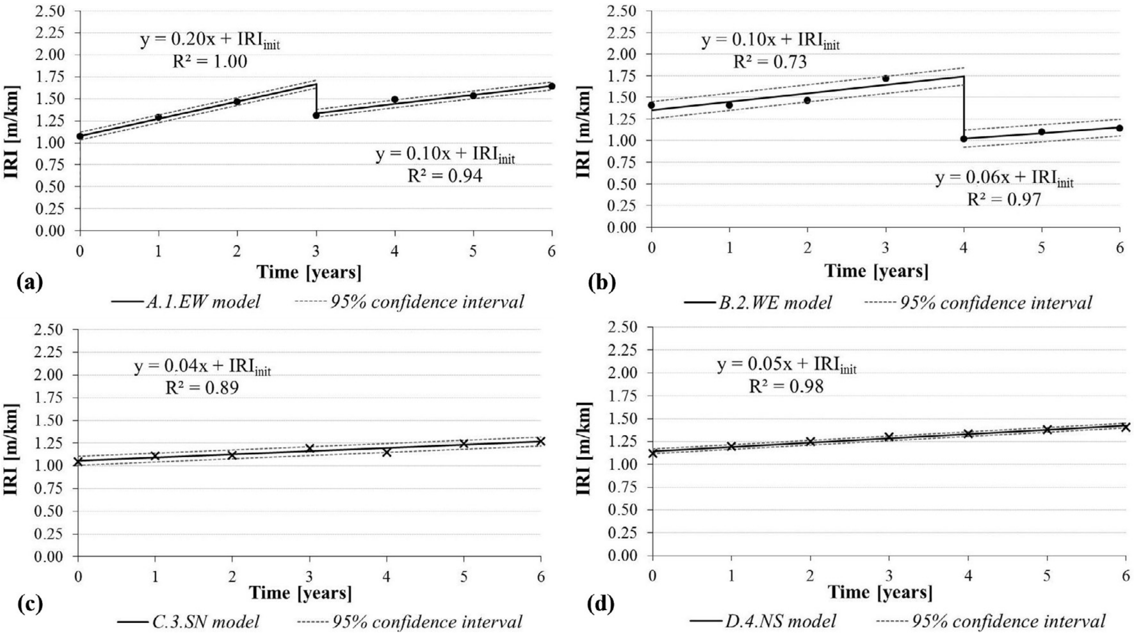

Fig. 7. IRI [m/km] degradation models.

the entire analysis period (2008–2014). The analyzed sections (lane width of 3.75 m) are summarized in Table 7.

Fig. 7 plots IRI values as a function of time (year 'zero' is the first year of the survey or the first year after a mill&fill maintenance treatment); Fig. 7(a) and (b) are related to Highway I while Fig. 7(c) and (d) refer to Highway II. The degradation curves revealed that roughness loss over time can be described by a linear function with great accuracy (IRI equation and 95% confidence interval are both shown in Fig. 7).

Highway II South-North direction (Macro-sector C) and Highway II North–South direction (Macro-sector D) displayed the same IRI trend over time, with similar initial IRI value of about 1.10 m/km and final values of 1.27 m/km and 1.41 m/km, respectively (Section 4 had a rapid decrease compared to Section 3).

The three performance indicators (SFC, IRI and MPD) highlighted a maintenance intervention for both directions of Highway I, with this being performed during the fourth year of monitoring (i.e., 2011), before the inspection on the East–West direction and after the survey on the West-East direction. No maintenance interventions can be found on Highway II, except for a surface treatment conducted on the South-North direction to improve friction in 2009.

Fig. 8 shows IRI [m/km] over CESALs. Highway I (Fig. 8(a) and (b)) and Highway II (Fig. 8(c) and (d)) presented the same trend for both directions, with maintenance treatment conducted on Highway I after almost 11 million ESALs.

5. Conclusions

Based on the data collection campaign between 2008 and 2014 conducted on major Italian highways, the following conclusions can be drawn.

- This research developed a methodology that was intended to be useful to Italian road agencies to analyze recorded high-quality survey data during monitoring campaigns and schedule maintenance and repair activities at project level, accordingly. Developing an inventory, monitoring assets, dividing the network into homogeneous sections from a geometrical and structural–functional point of view demonstrated to be an effective path toward the assessment of current pavement conditions and the prediction of future deterioration trends.

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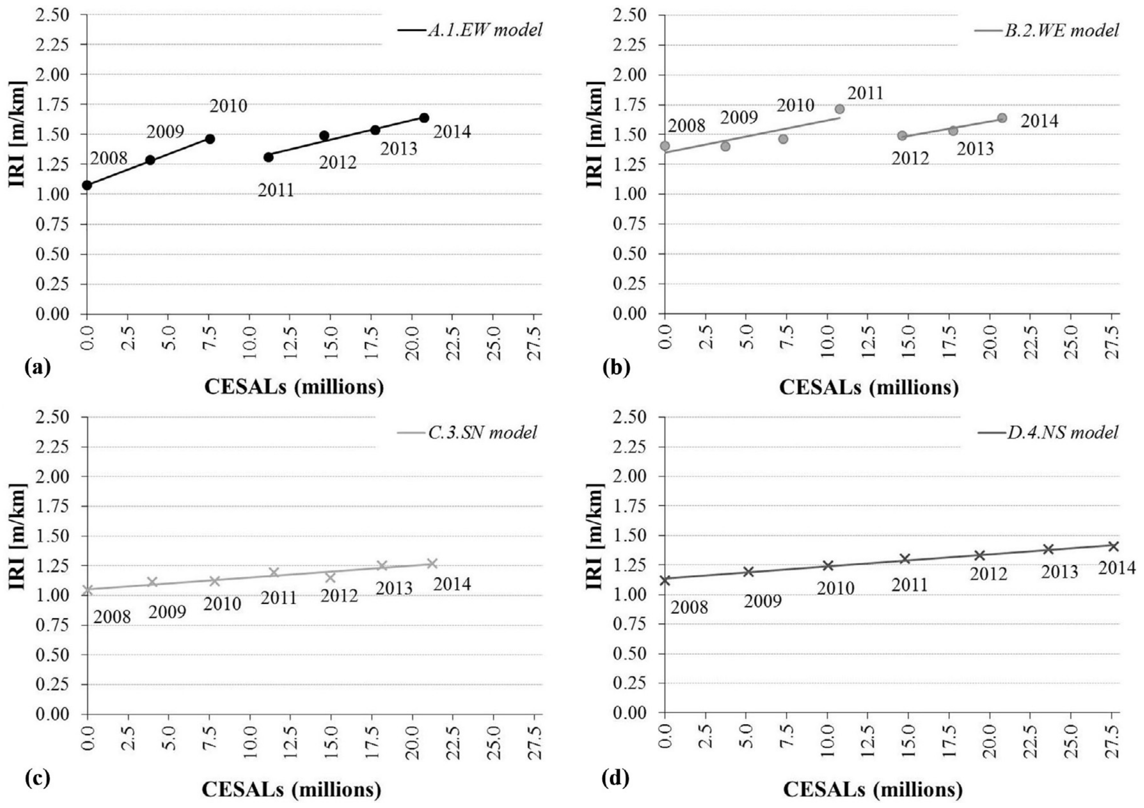

Fig. 8. International Roughness Index versus Cumulative ESALs.

- High-speed monitoring resulted to be a useful tool to investigate pavement conditions, describing the pavement actual behavior over time and spotting out maintenance treatments that were not recorded, providing an evaluation of their effectiveness.
- Pavement monitoring enables road agencies to rationally allocate resources, as one of the main advantages of inspection activities is the awareness of the best time for maintenance action. Based on the analysis process used in this research, accuracy and consistency of collected data is recommended during monitoring, in order to prevent errors and wrong performance forecasts.
- IRI [m/km] and SFC (60 km/h, 20 °C) deterioration functions were studied over time with their confidence intervals and MPD [mm] values were matched to the other surface properties.
- Due to cumulative traffic loading, pavement friction decreases while the International Roughness Index increases over time. At the studied project level, a good correlation between performance indicators and time was clearly shown for all road sections.
- The two highways were characterized by the same material and layer thickness; however, studying deterioration trends for Italian roads with different Structural Numbers and wearing course materials could be of interest in the future.
- Finally, since climatic conditions in Italy vary a lot from north to south and from coastal to mountain areas, different environmental conditions should be taken into consideration in future research.

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