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Analysis of IRI degradation components in HDM-4 under different climatic and structural conditions

Análise dos componentes de degradação do IRI no HDM-4 sob diferentes condições climáticas e estruturais

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ABSTRACT

The International Roughness Index (IRI) is one of the main indicators of pavement functional condition and serves as a key parameter for maintenance planning by road agencies. Preserving surface quality is directly related to user safety, ride comfort, and reduced operating costs. Therefore, predicting the evolution of IRI over time enables more efficient resource allocation and maintenance scheduling. This study aims to identify and quantify, through the Highway Development and Management (HDM-4) model, the contribution of IRI degradation mechanisms (environmental, structural, cracking, rutting, and potholing), considering variables such as climate, traffic volume, pavement type, structural number, and surface thickness. Five specific calibrations, derived from real road data, were analyzed in addition to the software's default calibration, under simulated scenarios without corrective maintenance. The results indicate that the combination of high temperatures and large thermal amplitudes accelerate environmental and structural degradation, while increased traffic volume intensifies the effects of cracking and rutting. Pavements with lower structural numbers and thinner surfaces exhibited faster IRI progression, highlighting the combined influence of climatic and structural conditions on pavement durability.

RESUMO

A irregularidade longitudinal (IRI) é um dos principais indicadores da condição funcional dos pavimentos e serve como parâmetro para o planejamento de manutenções pelas entidades rodoviárias. A preservação da qualidade da superfície viária está diretamente associada à segurança, ao conforto dos usuários e à redução dos custos operacionais. Assim, prever a evolução do IRI ao longo do tempo permite otimizar a alocação de recursos e o planejamento de intervenções. Este estudo tem como objetivo identificar e quantificar, por meio do modelo *Highway Development and Management* (HDM-4), a contribuição dos mecanismos de degradação do IRI (ambiental, estrutural, trincamento, afundamento e panelas), considerando variáveis como clima, volume de tráfego, tipo de pavimento, número estrutural e espessura de revestimento. Foram analisadas cinco calibrações específicas, obtidas a partir de dados reais de rodovias, além da calibração padrão do software, em cenários simulados sem manutenção corretiva. Os resultados indicam que a combinação entre altas temperaturas e maiores amplitudes térmicas acelera a degradação ambiental e estrutural, enquanto o aumento do tráfego intensifica os efeitos de trincamento e afundamento. Pavimentos com menor número estrutural e revestimento mais delgado apresentaram evolução mais rápida do IRI, evidenciando a influência conjunta das condições climáticas e estruturais na durabilidade dos pavimentos.

1. INTRODUCTION

International Roughness Index (IRI) is recognized as one of the main performance indicators for asphalt pavements, as it reflects variations in surface elevation that directly affect user comfort, road safety, and vehicle operating costs (Paterson, 1987). Predicting the evolution of the IRI over time enables the identification of surface deterioration patterns and the planning of more effective maintenance interventions, contributing to reduced operating costs and extending the pavement's service life (Huang, 2004).

Over the decades, several models have been developed to predict pavement degradation. Among them, the Highway Development and Management (HDM-4) model is globally used for performance analysis and highway maintenance planning (Thube, 2013). This software is applied at the network level in pavement management, featuring simplifications (particularly regarding the detailing of material parameters) which impose significant limitations for project-level applications.

HDM-4 models are incremental deterministic, meaning they predict the annual deterioration of specific parameters based on factors such as pavement type, climatic conditions, traffic volume and composition, and the quality of maintenance interventions (Bagui and Ghosh, 2015). Developed from road data from various countries, particularly developing nations, the software's default equations tend to produce rather aggressive projections, especially regarding roughness. Therefore, these models require calibration to ensure that their predictions are suited to local conditions, enhancing their effectiveness in decision-making for pavement preservation and rehabilitation strategies (Deori et al., 2016).

The need to understand the mechanisms of pavement deterioration, considering the distinct effects of climate and structural conditions, has been emphasized in several studies, particularly those focused on developing countries (Archondo-Callao, 2000; Deori et al., 2016). In Brazil, the National Department of Transport Infrastructure (DNIT) conducted in 2018 a calibration study of the HDM-4 equations for Brazilian highways at the network level, selecting experimental data from different climatic zones, surface types, and structural behaviors.

In HDM-4, the deterioration of longitudinal roughness is modeled as the sum of five components: environmental, structural, cracking, rutting, and potholing. The decomposition of IRI deterioration into these components allows for identifying which mechanisms are more sensitive to climatic variations and to the pavement's structural characteristics. Bannour et al. (2017) emphasized that the calibration of these components is crucial for accurately capturing local conditions, especially in countries with wide climatic and structural diversity.

This study aims to assess the influence of the different IRI deterioration components under various climatic and structural conditions, considering scenarios without corrective maintenance interventions. The proposed methodology seeks to integrate both theoretical and empirical advancements presented in the literature and the results from predictive model calibration and validation, contributing to a better understanding of pavement deterioration mechanisms related to roughness.

2. LITERATURE REVIEW

2.1. HDM-4 roughness model

The roughness model in HDM-4 consists of five components: environmental, structural, cracking, rutting, and potholing. Each component is modeled separately and has its own calibration factor (Morosiuk et al., 2004), as illustrated in Equation 1.

$$\Delta RI = \Delta RI_s + \Delta RI_c + \Delta RI_r + \Delta RI_p + \Delta RI_e \quad (1)$$

where: ΔRI : total incremental change in roughness during the analysis year, in m/km; ΔRI_s : incremental change in roughness due to structural deterioration during the analysis year, in m/km IRI; ΔRI_c : incremental change in roughness due to cracking during the analysis year, in m/km; ΔRI_r : incremental change in roughness due to rutting during the analysis year, in m/km; ΔRI_p : incremental change in roughness due to potholes, in m/km; ΔRI_e : incremental change in roughness due to environmental effects during the analysis year, in m/km.

2.1.1. Structural component

The structural component (ΔRI_s) of roughness in HDM-4 uses the adjusted structural number (SNP) as an indicator of pavement strength. Associated with the calibration factor K_{gs}, the structural component is a function of pavement age, adjusted structural number (SNP), and the traffic load acting on the road. The calibration factor for the environmental coefficient (K_{gm}) is used in the structural component model as a multiplier of pavement age.

The structural component of roughness in HDM-4 is represented in Equation 2:

$$\Delta RI_s = K_{gs}\, a_0\, exp\left[K_{gm}\left(m\right)\left(AGE3\right)\right]\left(1+SNPK_b\right)^{-5} YE4 \quad (2)$$

where: ΔRI_s : incremental change in roughness due to structural deterioration in the analysis year, in m/km; $SNPK_b$: adjusted structural number accounting for cracking at the end of the analysis year; $AGE3$: age since the last resurfacing or reconstruction, in years; $AGE3$: annual number of equivalent standard axles, in million/lane; m : environmental coefficient; K_{gm} : calibration factor for the environmental coefficient; K_{gs} : calibration factor for the structural roughness component; a_0 : fixed roughness component, in this case a_0 = 134.

2.1.2. Cracking component

The cracking component (ΔRI_c) of roughness in the HDM-4 model is a function of the incremental change in the total cracked area during the analysis year, associated with the calibration factor K_{gc} . Equation 3 represents the incremental increase in roughness due to cracking:

$$\Delta RI_c = K_{gc}\, a_0\, \Delta ACRA \quad (3)$$

where: ΔRI_c : incremental change in roughness due to cracking in the analysis year, in m/km; $\Delta ACRA$: incremental change in the total cracked area during the analysis year, in percent; K_{gc} : calibration factor for the cracking component of roughness; a_0 : fixed roughness component, in this case a_0 = 0.0066.

2.1.3. Rutting component

The incremental increase in roughness due to rutting in the HDM-4 model is a function of the standard deviation of rut depth, associated with the calibration factor K_{gr}.

The rutting component (ΔRI_r) of roughness in HDM-4 is given in Equation 4:

$$\Delta RI_r = K_{gr}\, a_0 \left(\Delta RDS\right) \quad (4)$$

where: ΔRI_r : incremental change in roughness due to rutting during the analysis year, in m/km; ΔRDS : incremental change in the standard deviation of rut depth during the analysis year, in mm; K_{gr} : calibration factor for the rutting component of roughness; a_0 : fixed roughness component, in this case a_0 = 0.088.

2.1.4. Potholing component

The potholing component (ΔRI_p) is a function of the number of potholes per kilometer of roadway and the driver's maneuvering freedom, and it is associated with the calibration factor K_{gp}. Paterson (1987) simulated the effects of potholes on roughness composition, considering both the occurrence and size of the potholes, as well as the vehicle's maneuvering freedom to take evasive actions, obtaining a strong correlation between these variables (Equation 5):

$$\Delta RI_p = K_{gp}\, a_0 \left(a1 - FM\right)\left[\left(NPT_{bu}\right)^{a_2} - \left(NPT_a\right)^{a_2}\right] \quad (5)$$

where: ΔRI_p : incremental change in roughness due to potholes on the pavement during the analysis year, in m/km; NPT_a : number of potholes per km at the beginning of the analysis year; NPT_{bu} : number of potholes per km at the end of the analysis year, as perceived by the road user; FM : freedom to manoeuvre index; K_{gp} : calibration factor for the potholing component of roughness; a_0 , a_1 and a_2 : fixed roughness components, in this case a_0 = 0.00019, a_1 = 2 and a_2 = 1.5.

2.1.5. Environmental component

The environmental component (ΔRI_e) of roughness in the HDM-4 model is a function of the initial roughness at the beginning of the analysis year and the environmental coefficient (*m*). It is associated with the calibration factor K_{gm}.

The environmental component of roughness in HDM-4 is represented in Equation 6:

$$\Delta RI_e = K_{gm}\, m\, RI_a \quad (6)$$

where: ΔRI_e : incremental change in roughness due to environmental effects during the analysis year, in m/km; RI_a : roughness at the beginning of the analysis year, in m/km; m : environmental coefficient; K_{gm} : calibration factor for the environmental component.

3. METHODOLOGY AND DATA

The data processing and all analyses were performed using HDM-4 software. Considering specific calibrations set based on real data, the roughness deterioration of new pavement sections was simulated over a 20-year period, without the occurrence of surface defects, and with an initial IRI value of 2.0 m/km. This value was defined based on the maximum IRI for new asphalt concrete pavements, according to DNIT 031/2024 (DNIT, 2024).

3.1. Variable definitions

The variables were defined based on technical and practical criteria that reflect the real conditions of Brazilian pavements and the characteristics of the study scenarios. Different combinations of climate, traffic level, pavement type, structural number, and asphalt layer thickness were evaluated, along with a comparison between the HDM-4 default calibration and specific calibrations sets for highways located in different climatic regions of Brazil. These definitions enable a comparative analysis of the individual and combined effects of each variable on pavement deterioration.

3.1.1. Specific calibrations

In this study, five specific calibrations were considered, based on real data, named C1, C2, C3, C4, and C5. These were developed from historical data of typical highways in the Brazilian federal network, which are in different climatic zones, with varying pavement conditions and subject to different traffic influences. The default HDM-4 calibration set, referred to as C0, was also evaluated.

For each calibration set, the calibration factors composing the roughness equation were defined: structural coefficient (K_{gs}), cracking (K_{gc}), rutting (K_{gr}), potholes (K_{gp}), and environmental (K_{gm}), components for which the equations are described in the theoretical framework. Table 1 presents the data for each of the calibrations evaluated.

3.1.2. Climatic zones

The calibrations set C0 through C5 were evaluated under the conditions of three Brazilian climatic zones: Central Brazil Tropical (TBC), Northeast Tropical (TNO), and Temperate (TEM) (IBGE, 2002). Calibration set C1 contains data from the TBC climate, C2 from the TNO climate, and the remaining calibrations, C3, C4, and C5, are associated with the TEM climate. The characteristics of each of the climatic zones used in HDM-4 are presented in Table 2.

3.1.3. Pavement type and structural characteristics

The pavement type was evaluated in two different configurations: asphalt pavement with a granular base (flexible) and asphalt pavement with a cemented base (semi-rigid). For both types, a new asphalt concrete layer (HMA) was considered, with variable thicknesses of 50, 100, and 150 mm, which directly influence the pavement deterioration equations.

The values of the Adjusted Structural Number (SNP) were set at 3.0, 5.0, and 7.0, representing low, medium, and high pavement strength structures, respectively. For semi-rigid pavement, a 20 cm thick cement stabilized aggregate base (CSAB) with a modulus of 10 GPa was considered.

Table 1: Calibration factors

Calibration Set	Pavement Type	Traffic Level	K_{gs}	K_{gc}	K_{gr}	K_{gp}	K_{gm}
C0	Flexible	Low	1.00	1.00	1.00	1.00	1.00
		Medium	1.00	1.00	1.00	1.00	1.00
		High	1.00	1.00	1.00	1.00	1.00
Default HDM-4	Semi-rigid	Low	1.00	1.00	1.00	1.00	1.00
		Medium	1.00	1.00	1.00	1.00	1.00
		High	1.00	1.00	1.00	1.00	1.00
C1	Flexible	Low	0.35	1.50	1.07	0.87	1.38
		Medium	0.59	1.95	1.62	0.97	1.29
		High	0.66	1.78	1.12	0.90	1.39
	Semi-rigid	Low	0.19	1.29	0.60	0.57	1.27
		Medium	0.52	1.25	1.48	0.74	1.34
		High	0.40	0.68	2.46	0.59	1.30
C2	Flexible	Low	1.22	1.36	1.95	1.48	1.53
		Medium	0.91	2.48	0.86	1.35	1.51
		High	0.91	2.48	0.86	1.35	1.51
	Semi-rigid	Low	0.52	2.06	1.44	1.05	1.55
		Medium	0.52	2.06	1.44	1.05	1.55
		High	0.52	2.06	1.44	1.05	1.55
C3	Flexible	Low	0.35	1.59	0.10	1.00	0.77
		Medium	0.71	1.28	0.94	1.00	1.04
		High	0.80	1.85	1.41	1.06	1.45
	Semi-rigid	Low	0.71	1.15	1.16	1.06	1.22
		Medium	0.71	1.15	1.16	1.06	1.22
		High	0.82	2.67	1.76	1.00	1.98
C4	Flexible	Low	1.18	2.02	2.35	1.00	1.87
		Medium	0.39	1.83	2.71	1.00	1.46
		High	0.39	1.83	2.71	1.00	1.46
	Semi-rigid	Low	1.18	2.02	2.35	1.00	1.87
		Medium	0.39	1.83	2.71	1.00	1.46
		High	0.39	1.83	2.71	1.00	1.46
C5	Flexible	Low	0.94	1.71	1.23	1.33	1.42
		Medium	0.46	2.37	1.81	1.23	1.71
		High	0.65	3.04	1.50	1.15	2.13
	Semi-rigid	Low	1.65	1.02	1.02	1.00	1.37
		Medium	0.61	2.93	2.93	1.21	1.69
		High	0.81	3.06	1.29	1.00	2.50

Table 2: Characteristics of each climatic zone

Climate Characteristics	Central Brazil Tropical (TBC)	Northeast Tropical (TNO)	Temperate (TEM)
Moisture Classification	Humid	Humid	Humid
Moisture Index (%)	69.7	75.9	78.9
Duration of dry season (months)	3.5	3.0	1.5
Mean monthly precipitation	95.2	72.9	153.7
Temperature Classification	Subtropical - hot	Tropical	Subtropical - hot
Mean temperature (°C)	24.7	26.3	20.0
Avg. Temperature Range (°C)	11.9	8.9	10.0
Days with Temp. > 32°C	87	79	28

Source: Adapted from DNIT (2018).

3.1.4. Vehicle fleet

Representative vehicles circulating on the Brazilian highway network were used, as listed in the Vehicle Manufacturers Register (QFV) of DNIT (2012) with corresponding data in the PNCT (Public Bid No. 811/2012). The adopted vehicle distribution, along with the description and the equivalent single axle load (ESAL) of these vehicles, is presented in Table 3.

Table 3: Representative Brazilian vehicle fleet

QFV Category (DNIT, 2012)	Description	Number of Axles	ESAL
2C	Light truck 2C, PNCT Class A2	2	2.56
2CB	Bus 2CB with two axles, PNCT Class A1	2	2.56
3C	Light truck 3C, PNCT Class B2	3	3.37
2DL	2DL, tractor truck + trailer, PNCT Class C6	4	6.50
2S2	2S2, tractor truck + semi-trailer, PNCT Class C2	4	5.34
2S3	2S3, tractor truck + semi-trailer, PNCT Class D1	5	6.55
3S3	3S3, twin-axle tractor truck + semi-trailer, PNCT Class E1	6	7.36
3D4	3D4, twin-axle truck + trailer, PNCT Class F2	7	8.92
3T4	3T4, twin-axle tractor truck + two semi-trailers, PNCT Class F3	7	8.92
3M6	3M6, twin-axle tractor truck + two trailers, PNCT Class H1	9	11.35

3.1.5. Traffic level

Traffic level was classified as Low (TB), Medium (TM), and High (TA). In terms of ESAL, the HDM-4 was configured with traffic corresponding to $1x10^6$ annual repetitions of the equivalent standard axle for Low Traffic. For Medium and High Traffic levels, $5x10^6$ and $1x10^7$ equivalent standard axle repetitions were used, respectively.

3.2. Data compilation

Once the input parameters and the calibration sets to be adopted were defined in the software, a database was generated through the combination of all these factors, representing different scenarios of interest and reflecting various real-world conditions for this study.

For the default calibration set (C0), combinations were created for the three climatic zones. The other calibrations were performed for highways located in specific climatic zones; therefore, each calibration (C1 to C5) was combined only with its corresponding climatic zone.

In total, 432 different combinations were generated, as shown in Table 4.

Table 4: Total combinations of study variables

Climatic Zone	Calibration Set	Traffic Level	Pavement Type	SNP	Surface Thickness (mm)
TBC	C0	TB	Flexible	3	50
TNO					
TEM					
TBC	C1				
TNO	C2	TM	Semi-rigid	5	100
TEM	C3	TA		7	150
	C4				
	C5				

4. RESULTS

The 432 scenarios were evaluated separately for each calibration set, observing the individual influence of each component on the composition of roughness degradation. In all combinations, variations in climate, traffic, structural number (SNP), and surface thickness were found to affect each component of IRI degradation. Climates with higher average temperatures and greater daily thermal amplitudes tend to accelerate environmental and structural mechanisms, causing these coefficients to have the greatest influence on the development of roughness. Similarly, higher traffic volumes intensify the effects of cracking and rutting. In general, pavements with lower SNP values and thinner asphalt layers exhibit faster roughness progression.

4.1. Default calibration set

To standardize the analyses, the IRI service life was equally divided into three periods. The total service life considered for each analysis was variable, being calculated from the beginning of the analysis until the point at which the HDM-4 degradation limit was reached (IRI = 16.0 m/km). However, for paved roads, IRI values around 5 m/km already represent critical trafficability conditions.

For example, a given analysis may have a total service life of 20 years, divided into approximately three 6-year periods, or 12 years divided into three 4-year periods. In this framework, the first third of the service life represents the initial years of degradation, while the last third represents the final years of the pavement's life.

Figure 1 shows the predicted roughness progression for the most representative scenarios analyzed under the HDM-4 default calibration set (C0). When assessing the different combinations, it is observed that during the early years of the pavement's service life, the component with the greatest impact on roughness varies. The environmental component represents the largest share of IRI degradation in pavements with medium and high structural strength (SNP = 5 and SNP = 7) when combined with low traffic levels (Figure 1a). Conversely, when the same pavements with medium and high strength are subjected to medium or high traffic levels, the rutting component becomes the main factor influencing roughness degradation (Figure 1b). Finally, pavements with SNP = 3 are more affected by the structural component in IRI degradation (Figure 1c). Moreover, variations in climate and pavement type (flexible or semi-rigid) did not show a significant influence on the variation of the degradation components.

During the intermediate years of the pavement's service life, the rutting component loses relevance to the environmental component in high-strength pavements (SNP = 7) and to the structural component in medium-strength pavements (SNP = 5) (Figure 1b and Figure 1a, respectively). At this stage, the structural component becomes the main contributor to IRI degradation. The cracking component appears as the predominant factor in only a few cases (2.5%), such as for semi-rigid pavements under high traffic and high strength. The rutting component remains dominant in 1.2% of the cases, where high traffic and high-strength pavements coincide with the Tropical Northeastern (TNO) climatic zone (Figure 1d).

In the final phase of the pavement's service life, potholes begin to appear, exerting a devastating effect on IRI degradation. Once the first potholes emerge, the progression of this functional parameter accelerates rapidly, reaching the HDM-4 limit (16.0 m/km) within a few years, as observed in all graphs of Figure 1. During this period, the environmental component still appears as the main factor in about 8% of the evaluated combinations, particularly in high-strength, low-traffic semi-rigid pavements. The structural component predominates in low-strength pavements (27%). Therefore, the pothole component is the main factor influencing IRI degradation at this stage, representing 65% of the analyzed cases.

The average contribution of each IRI deterioration component for all simulations using the HDM-4 default calibration set (C0) is presented in Figure 2. This figure shows the analysis through three charts, which represent the initial, intermediate, and final years of roughness progression.

4.2. Specific calibrations

The calibration set C1, corresponding to a highway located in the Tropical Central Brazil (TBC) climatic zone, showed a reversal in the influence of components on IRI deterioration when compared to the HDM-4 default calibration set (C0). For most of the analyzed combinations, the environmental component represents the largest share of roughness composition throughout all phases of the pavement's service life, followed by the structural component. Only in the final phase, the pothole component becomes the most significant contributor to IRI composition in 20% of the cases, as shown in Figure 3.

Similarly, the same reversal in the influence of components can be observed in Calibration C2, corresponding to a highway located in the Tropical Northeastern (TNO) climatic zone. Figure 4 presents the average contribution of the deterioration components during the initial, intermediate, and final phases of this calibration.

The environmental component was the main factor in IRI deterioration during the initial and intermediate phases of the pavement's service life, followed by the structural component. In this climatic zone, the rutting component also plays an important role in degradation during the initial phase, particularly for pavements with good structural strength. In the final phase of the service life, another reversal occurs, with the structural component becoming the largest contributor, followed by the environmental component. During this phase, the pothole component accounts for the largest share of deterioration in 19% of cases.

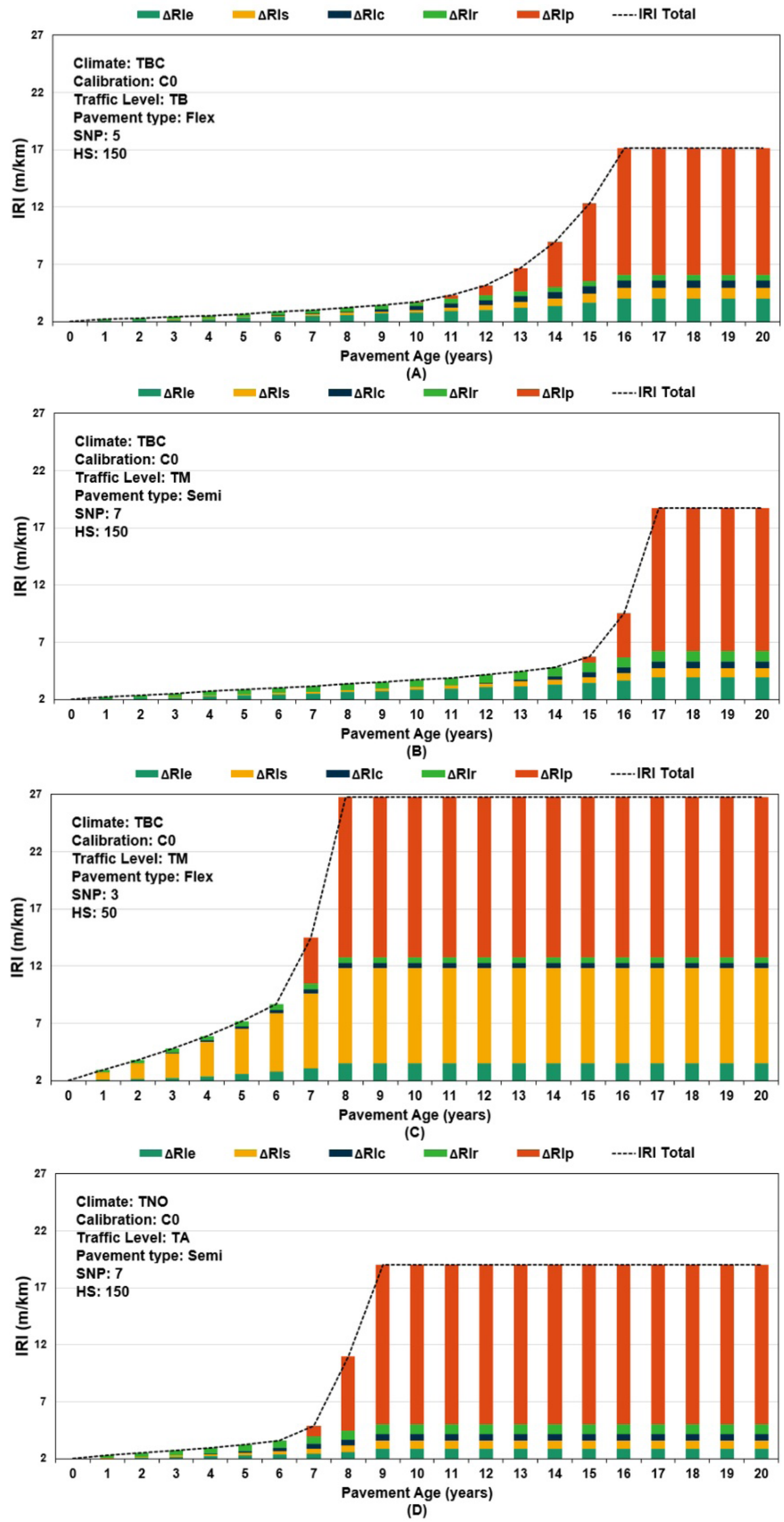

Figure 1. Progression under different combinations: (a) TBC, C0, TB, Flex, SNP=5, HS=150 Combination (b) TBC, C0, TM, Semi, SNP=7, HS=150 Combination (c) TBC, C0, TM, Flex, SNP=3, HS=50 Combination (d) TNO, C0, TA, Semi, SNP=7, HS=150 Combination.

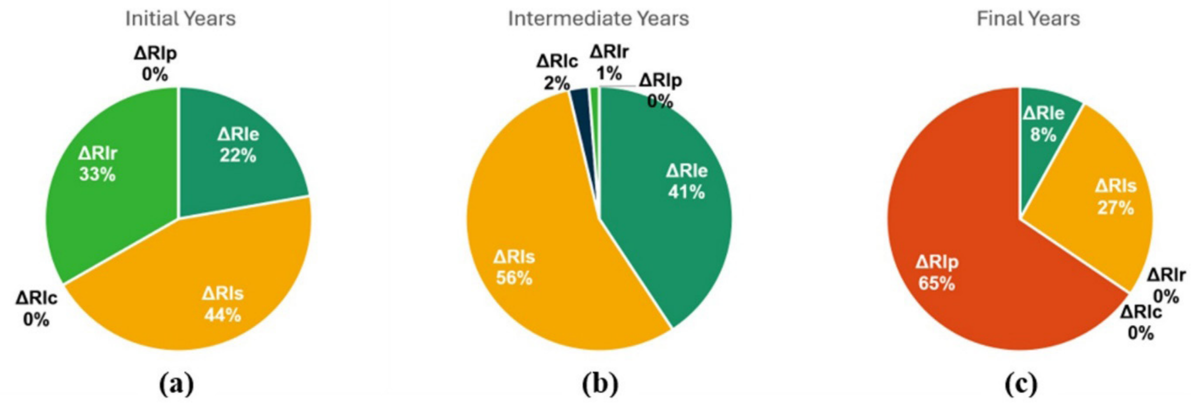

Figure 2. Average contribution of deterioration components – Calibration Set C0 with component contribution (a) Initial years (b) Intermediate years (c) Final years.

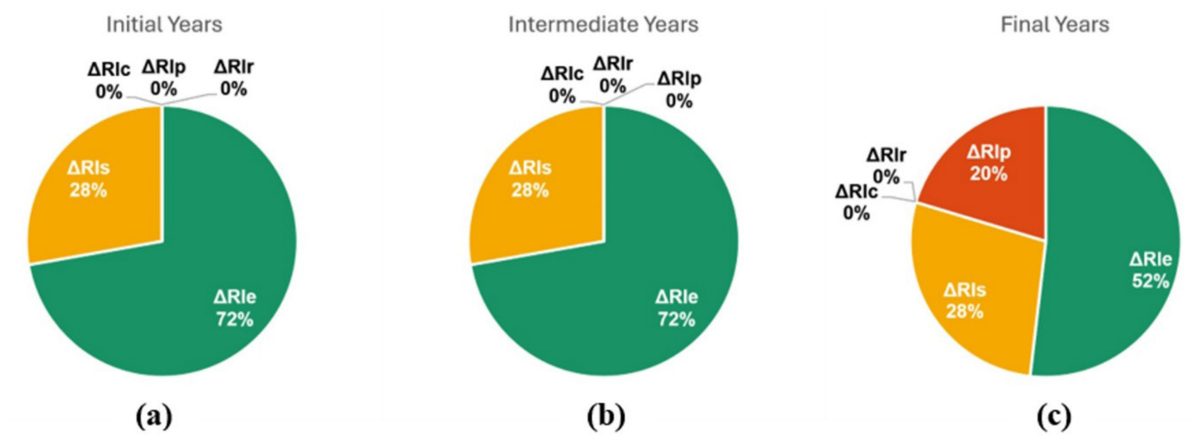

Figure 3. Average contribution of deterioration components – Calibration Set C1 with component contribution (a) Initial years (b) Intermediate years (c) Final years.

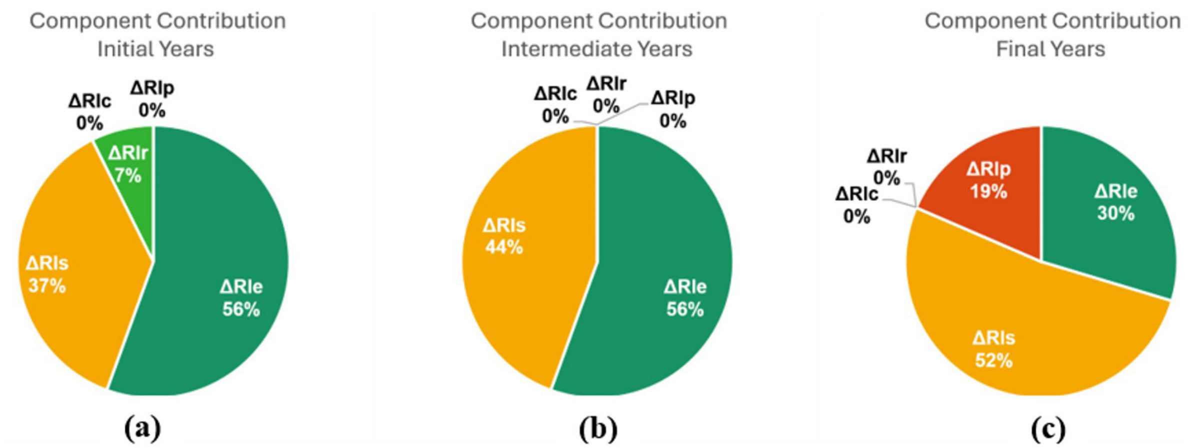

Figure 4. Average contribution of deterioration components – Calibration Set C2 with component contribution (a) Initial years (b) Intermediate years (c) Final years.

The highways corresponding to Calibrations C3, C4, and C5 are in the Temperate climatic zone. **The average contributions of each roughness component during the initial, intermediate, and final phases for Calibrations C3, C4, and C5 are shown in** Figures 5 a, b and c, respectively.

In all cases, the environmental component accounts for the largest share of IRI deterioration in the initial phase, followed by the structural component. In the final phase of deterioration, a reversal occurs in Calibrations C3 and C5, where the structural component becomes the main contributor. In Calibration C4, this reversal does not occur, and the environmental component remains the dominant factor throughout the analysis period.

Regarding the pothole component, it represents the largest share of IRI deterioration in 15% of cases for Calibration C3 and appears less prominently in Calibrations C4 and C5, with 7% and 3% o f the cases, respectively.

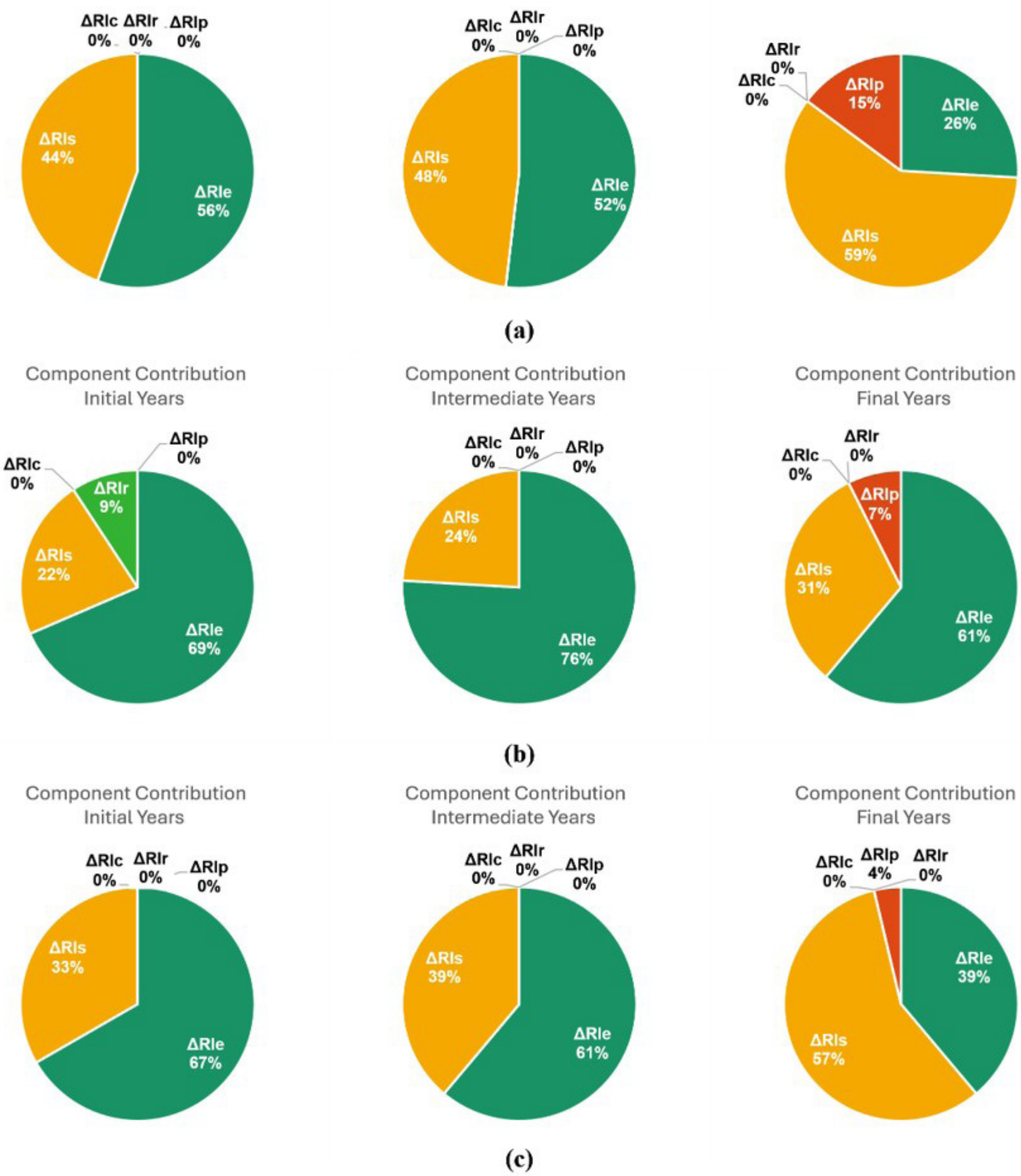

Figure 5. Average contribution of deterioration components for calibrations sets (a) C3 (b) C4 and (c) C5.

5. CONCLUSIONS

The analyses carried out in this study demonstrated that, for most combinations of climate, calibration, pavement type, and structure, the environmental component exerts the greatest influence on IRI deterioration during the early stages of the pavement's service life, while the structural component becomes more relevant as the pavement ages. The pothole component becomes more significant as the pavement approaches the IRI limit at the end of the analysis period. Overall, IRI deterioration was found to be highly dependent on the pavement's structural condition and the traffic load. Although the environmental component plays an important role in IRI evolution, climate variation had little impact on its changes. Surface distresses such as rutting and cracking were found to have a less pronounced effect on IRI progression.

From a management perspective, the results indicate that the HDM-4 default calibration set (C0) may, in certain situations, underestimate or overestimate the actual deterioration of asphalt pavements, depending on local conditions. In contrast, the specific calibrations (C1 to C5) allow for a better adjustment of the roughness deterioration model to situations, providing more reliable predictions. The calibrations obtained from this study generally made the models more dependent on highway and pavement characteristics (environmental and structural components) and less influenced by surface conditions (cracking and rutting).

AUTHORS' CONTRIBUTIONS

DRA: Formal analysis, Methodology, Writing – original draft; CYZ: Supervision; CM: Methodology, Writing – review & editing.

CONFLICTS OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence tools were used in the research reported here or in the preparation of this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon request.

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