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Use of the HDM-4 in feasibility studies for highway concessions: traffic influence on maintenance cycles

Uso do HDM-4 nos estudos de viabilidade de concessões rodoviárias: influência do tráfego nos ciclos de manutenções

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ABSTRACT
Traffic variables and subgrade bearing capacity are key factors in the mechanistic-empirical design of flexible pavements. However, the lack of accurate data makes estimating traffic loads a challenging task. This study analyzes the influence of traffic on maintenance needs and the service life of road pavements, using HDM-4 performance prediction models applied to Brazilian highway concessions. It also evaluates the impacts of the 2021 Weight Regulation Law on pavement performance and intervention cycles. Nine pavement structures were analyzed under different traffic and subgrade conditions, monitoring the evolution of roughness and cracking over a 30-year concession period. A scenario considering overloads allowed by Law No. 14.229/2021 was included for comparison. Based on these results, a preliminary economic analysis was carried out, estimating cumulative maintenance costs by type of intervention. The results indicate that higher traffic volumes significantly accelerate pavement deterioration and that recent legal changes may increase maintenance costs by up to 25%, compromising structural quality. Therefore, the study highlights the importance of proper planning and well-designed interventions in the face of growing traffic and regulatory changes to ensure the performance and safety of concessioned pavements.

RESUMO
As variáveis de tráfego e a capacidade de suporte do subleito são fatores centrais no dimensionamento mecanístico-empírico de pavimentos flexíveis. No entanto, a falta de dados precisos torna desafiadora a estimativa das cargas de tráfego. Este estudo analisa a influência do tráfego nas manutenções e na vida útil de pavimentos rodoviários, utilizando modelos do HDM-4 em concessões brasileiras. Também são avaliados os impactos da Lei da Balança de 2021 sobre o desempenho e os ciclos de intervenção do pavimento. Foram analisadas nove estruturas com diferentes cenários de tráfego e subleito, observando-se a evolução da irregularidade e do trincamento em 30 anos de concessão. Um cenário com sobrecargas permitidas pela Lei nº 14.229/2021 foi incluído para comparação. Com base nisso, realizou-se uma análise econômica preliminar, estimando os custos acumulados de manutenção por tipo de intervenção. Os resultados indicam que maiores volumes de tráfego aceleram a deterioração do pavimento e que a alteração legal mais recente pode elevar os custos de manutenção em até 25%, comprometendo a qualidade estrutural. Assim, o estudo reforça a importância do planejamento adequado e de intervenções bem dimensionadas diante do crescimento do tráfego e das mudanças regulatórias para garantir o desempenho e a segurança dos pavimentos concessionados.

1. INTRODUCTION

The road mode is the primary means of transportation used in Brazil and has a significant influence on the country's economy. However, compared to other areas of civil construction, pavement projects have a relatively shorter service life, usually around 10 years for asphalt pavements and 20 for concrete pavements. This is due to the limited number of cycles the commonly used materials can withstand and the difficulty in predicting the effects of traffic and climate (Fonseca and Motta, 2013).

The commercial vehicle traffic adopted for the project's service life significantly influences the determination of a pavement structure, along with the subgrade's bearing capacity, being the determining factors for the mechanistic-empirical design of flexible road pavements. Additionally, repeated traffic loads are the main cause of pavement deterioration and their maintenance frequency. However, predicting traffic characteristics over the design period is seen as a major challenge, as it is uncertain and does not always reflect reality (Vallejo, 2021).

This challenge becomes more critical due to successive changes in Brazilian legislation since 1964, the year when the regulation of heavy vehicle traffic and maximum axle load limits were first established. However, it was with Law No. 7.408/1985 that a 5% tolerance for these limits was introduced. Later, in 1994, CONTRAN clarified that this tolerance applied exclusively to weighings performed using road scales. In 1999, Resolutions No. 102 and 104 increased the axle overload tolerance to 7.5%, maintaining the 5% only for Total Gross Weight and Combined Total Gross Weight, defining penalties only when these limits were exceeded.

From the 2000s onward, with new discussions about the effects of these tolerances, Resolution No. 258/2007 reaffirmed the 5% margin to compensate for equipment uncertainty. In 2014, Resolution No. 489 revised this article and established three tolerance ranges: 5% for Total Gross Weight, Combined Total Gross Weight and Maximum Traction Capacity; 7.5% per axle when Total Gross Weight is exceeded; and 10% per axle when Total Gross Weight is not exceeded. In 2015, Resolution No. 526 standardized the axle tolerance at 10% and allowed travel continuation when the excess did not exceed 12.5%. Finally, in 2021, Law No. 14.229 increased the axle tolerance to 12.5% and restricted enforcement to Total Gross Weight or Combined Total Gross Weight for vehicles under 50 tons-force (Brasil, 2021).

These changes, initially created to deal with weighing inaccuracies, were gradually interpreted as operational margins by the transportation sector. This resulted in overloads that directly affect pavement durability. Older projects, designed under stricter limits, may not withstand these new conditions, which could compromise their service life and lead to more frequent maintenance.

Thus, for pavement projects to perform well throughout their service life, there must be control and planning of their maintenance, i.e., the application of a Pavement Management System (PMS) for all stages of the project's service life (Ramos, Cavaignac and Gonzalez, 2020). Countries that do not maintain their infrastructure appropriately, allowing premature deterioration, will face increased costs of the order of 1 to 3% of the national Gross Domestic Product (GDP), besides affecting user safety and comfort (Macea-Mercado et al., 2016).

However, it is known that in the current national scenario over the past decades, interventions in the Brazilian road network, when they occur, are often delayed and insufficient for the pavement's condition. Research conducted in 2023 by the National Transport Confederation (*Confederação Nacional do Transporte* - CNT) identified a 32.7% increase in road transport operating costs due to poorly maintained pavements (CNT, 2023).

In response to this situation, the government began, in 1993, a concession process for various federal highways to private companies or consortia, aiming to manage and expand the Brazilian road network within a defined timeframe. Consequently, within the 2023 Federal Highway Concession Program (*Programa de Concessões de Rodovias Federais* - PROCROFE), notices and agreements regarding concessions, and, more recently, re-tendering of previously concessioned highways, were published by the Ministry of Transportation (Brasil, 2023).

Due to the great need for better road planning, several programs have emerged to assist in the use of the PMS tool, such as the software developed by the World Bank, called HDM-4 (Highway Development and Management). In this program, it is possible to input different project and traffic data variables and develop a schedule with all necessary interventions throughout its service life to maintain adequate levels of comfort and safety service (Morosiuk, Riley and Odoki, 2004).

The program's origin dates to the late 1960s when the first studies on highway design and maintenance began. In 1976, the first version of the model, HDM, was launched, followed by HDM-III, which was widely used for over 20 years. With the evolution of technical, geographical, and environmental needs, HDM-4 emerged in the 2000s, a more advanced version that incorporated new pavement types, extreme climatic conditions, road safety analysis, environmental impacts, and traffic jams, becoming a more comprehensive and modern tool for planning and managing highway infrastructure (Nascimento, 2005).

Given this context, it becomes essential to rigorously and scientifically evaluate the hypothesis that legislative changes, specifically the change in axle load limit, may impact pavement maintenance and rehabilitation cycles, influencing durability and operational costs. This hypothesis assumes that changes in traffic rules, by altering the level of demands on the road structure, directly affect the frequency and intensity of necessary interventions to maintain adequate performance levels.

Although there are studies addressing the impact of overloads on pavements, the literature still lacks in-depth analyses correlating recent legislative changes with the actual performance and maintenance cycles of Brazilian highways. Thus, the scientific gap this study aims to fill is the quantitative and qualitative assessment of the influence of the 2021 Weight Regulation Law on the maintenance cycles of concessioned highways, using simulations through the HDM-4 performance prediction models, which allow an integrated analysis of design and traffic variables.

Therefore, the objective of this article is to analyze the influence of traffic variability, due to the new 2021 Weight Regulation Law, on maintenance cycles and structural performance of road pavements under concession regimes through simulations in the HDM-4 software. Additionally, it aims to estimate, in a preliminary and parametric manner, the economic impacts of these changes on maintenance strategies, contributing to the development of more robust technical and financial criteria in the planning and feasibility of concession contracts.

2. METHODOLOGY

The study was developed parametrically by defining different scenarios to represent a wide range of conditions present in the Brazilian road network. For this, different flexible pavement structures were defined, and based on the HDM-4 performance models, it was possible to analyze and compare the various ways in which deterioration parameters evolve, as well as investigate their possible causes. Finally, the effects of increased axle overload resulting from the new Weight Regulation Law were evaluated. Figure 1 illustrates the flowchart of the methodology used in the development of the research, which will be detailed in sections 2.1 and 2.2.

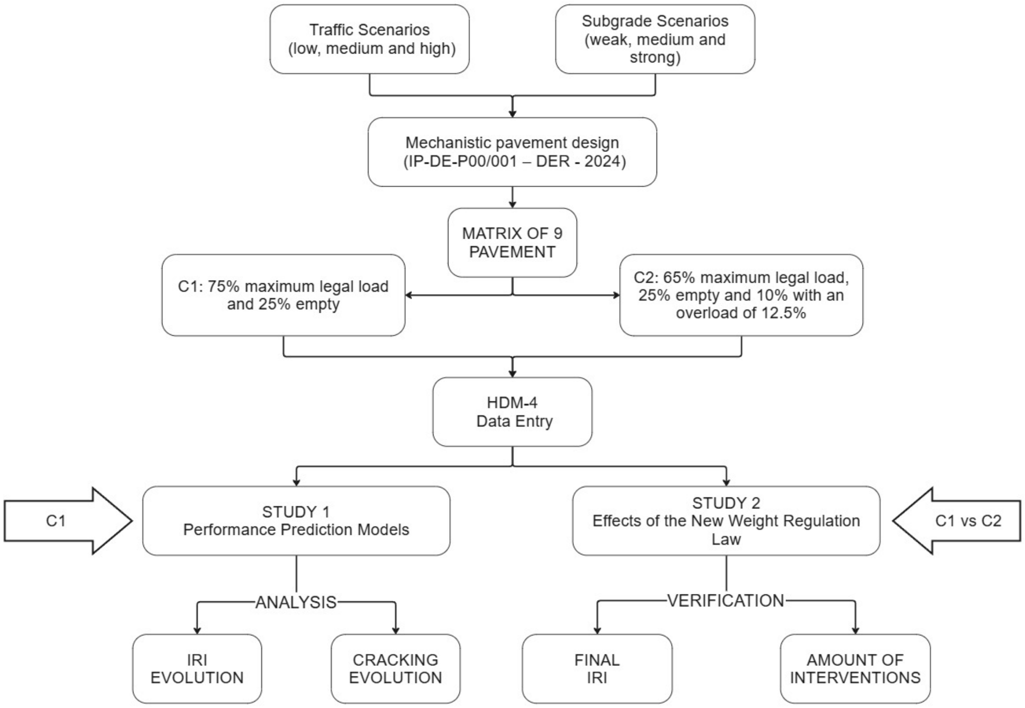

Figure 1. Research methodology flowchart.

2.1. Materials

This study was developed using a series of alternative pavement structures in different combinations to cover most possible cases. Based on the main variables influencing pavement design, three traffic scenarios were determined: low (LT), medium (MT), and high (HT), and three subgrade scenarios: strong (CBR=15%), medium (CBR=10%), and weak (CBR=5%), and a matrix of different pavements designed for each situation was assembled. For the values of subgrade elastic modulus, the correlation of Heukelom and Klomp (1962) was adopted, which multiplies the CBR value by 100 to obtain the modulus in kgf/cm^2. For the analysis of traffic variation, the three levels of traffic were defined based on the National Department of Transportation Infrastructure (*Departamento Nacional de Infraestrutura de Transportes* - DNIT) Basic Road Implementation Manual, where projects are classified according to Annual Average Daily Traffic (AADT) and are shown in Table 1 (DNIT, 2010).

Table 1: Project Class – DNIT (adapted from DNIT, 2010)

Project Class	Traffic Level	AADT
I	High	> 1400
II	Medium	1400 a 700
III	Low	700 a 300

The composition of each traffic scenario was made from a fleet with commercial vehicles varying from 2 to 9 axles. The Equivalent Standard Axle Load Factor (ESALF) of each vehicle was calculated by the HDM-4 program equation, with an exponent of 4, considering 75% of the vehicles with Maximum Legal Load and the remaining 25% empty. This composition was named case C1 for comparison purposes. The AADT values were first established for the medium traffic scenario and the other scenarios were defined proportionally. The calculation of the Number of ESALs (Equivalent Single Axle Loads) was performed considering an annual growth rate of 3%, according to usual economic projection estimates verified in our country. The characterization of each traffic scenario is described in Table 2.

Table 2: Characterization of each traffic scenario

Number of axles	Equivalent Standard Axle Load Factor (ESALF)	AADT		
		LT	MT	HT
2 axles	2.25	256	512	2560
3 axles	2.95	125	250	1250
4 axles	4.67	5	10	50
5 axles	5.73	5	10	50
6 axles	6.43	3	5	25
7 axles	7.79	2	5	25
8 axles	8.85	2	4	20
9 axles	10.24	2	4	20
Total AADT:		400	800	4000
Number of ESALs:		5.0E+06	1.0E+07	5.0E+07

With each scenario determined, it was possible to design nine different structures that were used in the development of the research. Initially, the structures with intermediate subgrade (CBR=10%) were chosen to be designed and from these three structures, the thicknesses of base and sub-base were replicated for the other subgrade scenarios and the minimum thicknesses of surface layer were calculated for the other situations. For the design of the structures, a mechanistic analysis was used, in which the allowable stresses were applied through widely disseminated fatigue models determined by The State Department of Highways (*Departamento de Estradas de Rodagem* – DER, 2024).

For the verification of fatigue cracking in the asphalt concrete layer, two types of fatigue models were used: the first is based on surface displacement, through The National Department of Highways (*Departamento Nacional de Estradas de Rodagem* - DNER, 1979), calculating the deflection at the top of the surface layer from the Number of ESALs, and the second is based on horizontal tensile strain at the bottom of the surface layer by the Federal Highway Administration (FHWA, 1976) method. Finally, the vertical strain at the top of the subgrade was verified, as this parameter is related to the plastic deformation suffered by the structure after a certain number of load applications. This verification is carried out according to the Shell KSLA (Koninklijke Shell Laboratorium Amsterdam) model – Dormon and Metcalf (1965).

Another important characteristic of the pavements used as input data for HDM-4 is the Structural Number (SN). The concept of SN was first used from the studies conducted by the AASHO Road Test in 1962 and emerged as a measure of pavement strength, entering the equations for the design of flexible pavements developed in the study, and in many others that followed (AASHO, 1972).

Therefore, the SN represents the overall structural requirements of the pavement section, being considered as an indicator of the pavement's stability under an applied load. The value of SN depends on the type of material, thickness, and drainage capacity of each pavement layer. However, in the study conducted by the AASHO Road Test in 1993, it was not possible to include the influence of the subgrade in the Structural Number or the influence of the depth of each pavement layer on the SN value. Thus, the concept called Adjusted Structural Number (SNPK) emerged to incorporate these particularities and provide more accurate results.

Thus, Table 3 presents the main characteristics of each designed structure. The “Section” column indicates the nomenclature of each designed structure, classifying them into traffic levels: LT (low traffic), MT (medium traffic), HT (high traffic) and into subgrade scenarios: 15%, 10%, and 5%. In the same column, the SN values calculated according to the AASHTO (1993) methodology in inches are indicated in parentheses, to be subsequently converted into SNPK with the defined subgrade characteristics. For the high traffic cases, an SN equal to 7 inches was adopted due to a limitation of the HDM-4 program to avoid distorting the performance prediction models in the case of very robust pavements.

Table 3: Pavement structure matrix

		Strong CBR = 15%		Medium CBR = 10%		Weak CBR = 5%	
Traffic	**Material**	**Thickness (cm)**	**Section (SN in.)**	**Thickness (cm)**	**Section (SN in.)**	**Thickness (cm)**	**Section (SN in.)**
Low (5E+06)	Bituminous pavement	9.5	LT-15 (4.25)	10.0	LT-10 (4.34)	13.0	LT-5 (4.86)
	Granular base	20.0		20.0		20.0	
	Subbase	20.0		20.0		20.0	
Medium (1E+07)	Bituminous pavement	12.5	MT-15 (5.11)	13.0	MT-10 (5.20)	17.0	MT-5 (5.89)
	Granular base	20.0		20.0		20.0	
	Subbase	25.0		25.0		25.0	
High (5E+07)	Bituminous pavement	19.0	HT-15 (9.86)	20.0	HT-10 (10.03)	20.5	HT-5 (10.12)
	Granular base	40.0		40.0		40.0	
	Subbase	60.0		60.0		60.0	

Finally, to analyze the effects of the new Weight Regulation Law, a specific scenario was determined for each traffic level called case C2, considering that 65% of the vehicles travel with Maximum Legal Load, 25% travel empty, and the remaining 10% will travel with the overload of 12.5% allowed by Law No. 14.229/2021. Therefore, the ESALF values of each vehicle were recalculated and are indicated in Table 4.

Table 4: ESALF values for each vehicle

	Number of Axles							
Cases	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Base (C1)	2.25	2.95	4.67	5.73	6.43	7.79	8.85	10.24
Overload of 12.5% (C2)	2.43	3.18	5.04	6.19	6.94	8.41	9.56	11.03

2.2. Methods

The computational program HDM-4 chosen for the study is frequently used as a PMS tool and aims to provide information about highway design over its service life and thus assist in decision-making regarding maintenance and rehabilitation activities, with minimal cost and in a way that ensures that the pavement condition remains within an acceptable standard. Also, HDM-4 adapts to different environments and scenarios through customization, which ensures a closer approximation to the reality of the study (Nunes, 2012).

For the purpose of the study, other variables were defined so that the nine structures would fit into the same scenario and only the unknowns of pavement structure, traffic, and subgrade would be different in each situation to better verify their influence on the models and performance prediction. Therefore, a standard geometry was adopted for all cases as bendy and gently undulating, with a double lane and shoulder on both sides, with quality of construction, compaction, surface, and texture all at good levels.

The International Roughness Index (IRI) for year 0 was adopted as 1.90 m/km, which, according to the Ministry of Infrastructure (Brasil, 2022), corresponds to an excellent level of IRI. In addition, the program has a configuration to choose what the IRI will be after maintenance, and for this study, the same value of 1.90 m/km was adopted for all cases studied. That is, the maintenance carried out will guarantee, in these scenarios, an excellent level of roughness after its execution.

These maintenance actions will be carried out based on the three main triggers that appear in the Highway Operation Program (*Programa de Exploração da Rodovia* - PER) of the fourth stage of federal highway concessions under the Federal Highway Concessions Program (PROCROFE): roughness greater than 2.70 m/km; cracked area greater than 7%; and rutting greater than 5 mm. In addition, three of the most common maintenance actions were adopted to be considered in all scenarios: milling of 3.0 cm with overlay of the same 3.0 cm (F3R3); milling of 4.0 cm with overlay of 4.0 cm (F4R4); and milling of 5.0 cm with overlay of 5.0 cm (F5R5).

For the medium and low traffic scenarios, it was decided to include structures with granular bases in the program and with an asphalt surface course in a single layer, while for the high traffic cases, the cases referred to by the program as “asphalt pavement bases” were adopted, i.e., when a granular base pavement is overlaid, having an older asphalt surface layer and a newer one. For this reason, only the high traffic structures had their surface layer thicknesses divided into two parts, with the older thickness always being equal to 10 cm.

Finally, with all the structural data entered into the HDM-4 program, two more scenarios of annual traffic growth rate were adopted: 1% and 5%, for the purposes of comparison and expansion of the study analysis, one being higher and the other lower than the rate used for the calculation of the designed Number of ESALs. The study analysis period was set at 30 years, as this is usually the duration of concessions.

3. RESULTS

3.1. Performance prediction models

From the study of the nine designed structures in the three annual growth rate scenarios (1%, 3%, and 5%) and with the three different maintenance actions (F3R3, F4R4, F5R5), 81 distinct outputs were obtained. For each output, it is possible to verify the evolution of traffic, structural number, and the HDM-4 performance prediction models, such as roughness and cracking.

Firstly, by analyzing the IRI progression model, there are several variables that modify it, accelerating or slowing its evolution. Regarding the subgrade CBR, which is included in the HDM-4 roughness progression model through the SNPK parameter, it is possible to note that its variation provides changes in the evolution of IRI over the years.

As shown in Figure 2, which presents all cases with low traffic, it is noted that the progression of roughness is more pronounced in cases of low CBR. However, in the low traffic scenario and low annual growth rate (1%), the subgrade exerts limited influence on the evolution of IRI, as the variation of roughness values for high, medium, and low CBR cases was very small, practically showing the same progression over the 30 years analyzed.

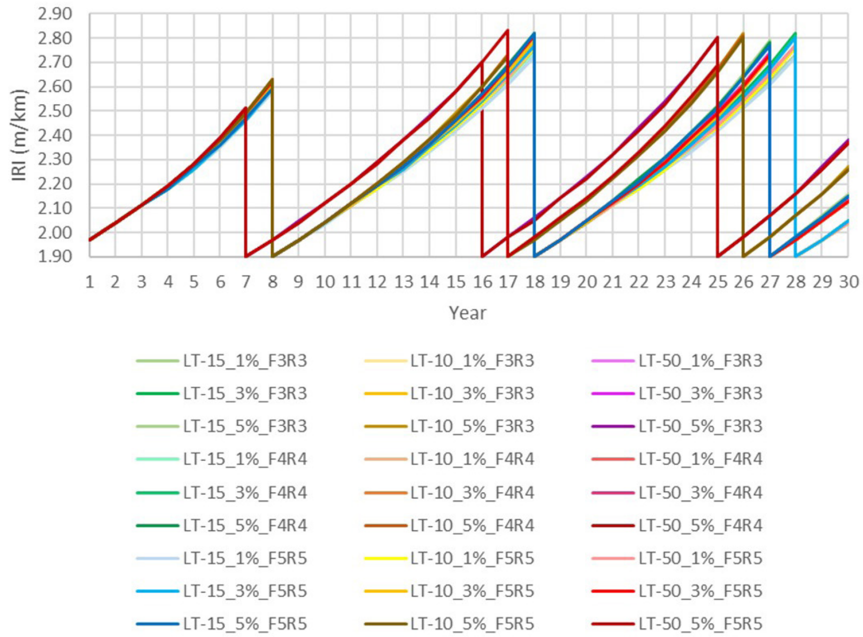

Figure 2. Evolution of IRI for low traffic scenarios.

On the other extreme, the high traffic scenario with a high annual growth rate (5%), presented in Figure 3, shows that the evolution of IRI over the 30 years indicates a greater variability, where the stronger subgrade (CBR=15%) shows a slower progression of roughness compared to the weaker subgrade (CBR=5%), which was already expected. Therefore, it can be concluded that for the roughness parameter, the subgrade will have a greater influence in situations of heavier traffic.

In addition, it is observed that the different maintenance thicknesses influence the evolution of roughness, but this influence is greater in the high traffic scenarios and more noticeable after 15 years of service life. This lesser influence of maintenance thickness in the study occurs due to the adoption of an IRI of 1.90 m/km after maintenance. It is also noticeable that the variation of traffic influences the number of interventions over the 30 years of the study and the interval between each maintenance, where for a low traffic scenario there are always three interventions regardless of CBR, but for higher traffic, the number of interventions increases to four or five over the 30 years of the study.

In Figure 4, the curves of the weak subgrade scenarios are shown, comparing the evolution of roughness as a function of traffic (high, medium, and low) and the annual growth rate, both directly influencing the Number of ESALs and consequently the behavior of IRI. It is observed that, in the first 10 years, there is a clear formation of three distinct evolution bands, corresponding to each traffic level, with the influence of the annual growth rate being less significant than the traffic level. It is highlighted that the lowest IRI values, among the initial growth curves, occur in the low traffic scenario with a 1% annual growth rate, as expected.

In addition, an inversion effect between high and medium traffic is perceived, where the medium traffic curves show higher values and a more accelerated evolution than the high traffic curves. However, this inversion does not occur in the evolution of the SNPK curve, as seen in Figure 5.

This phenomenon of inversion in the evolution of IRI occurs due to the environmental component of the HDM-4 evolution model, with all other unknowns that affect the progression of roughness (traffic and SNPK) being greater in the high traffic situation (DNIT, 2018). According to the model formulation, the environmental component has a greater influence on the progression of roughness (Morosiuk, Riley and Odoki, 2004).

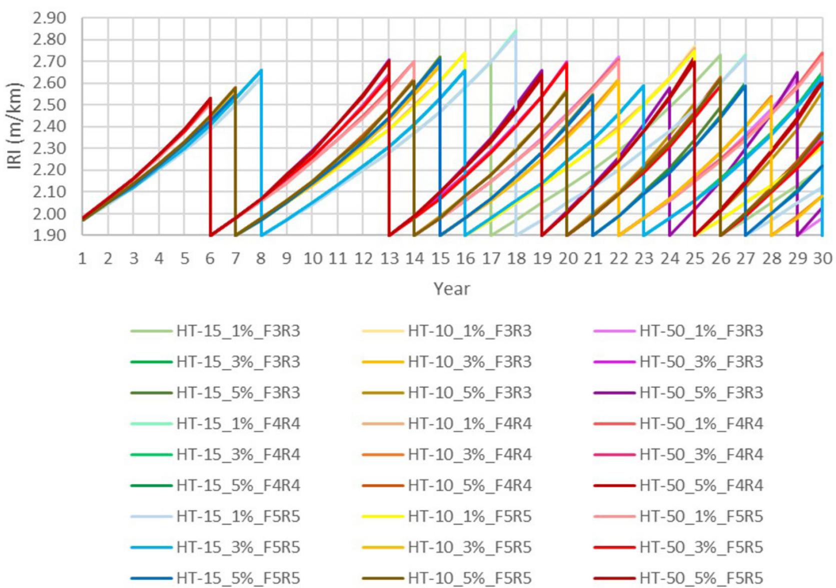

Figure 3. Evolution of IRI for high traffic scenarios.

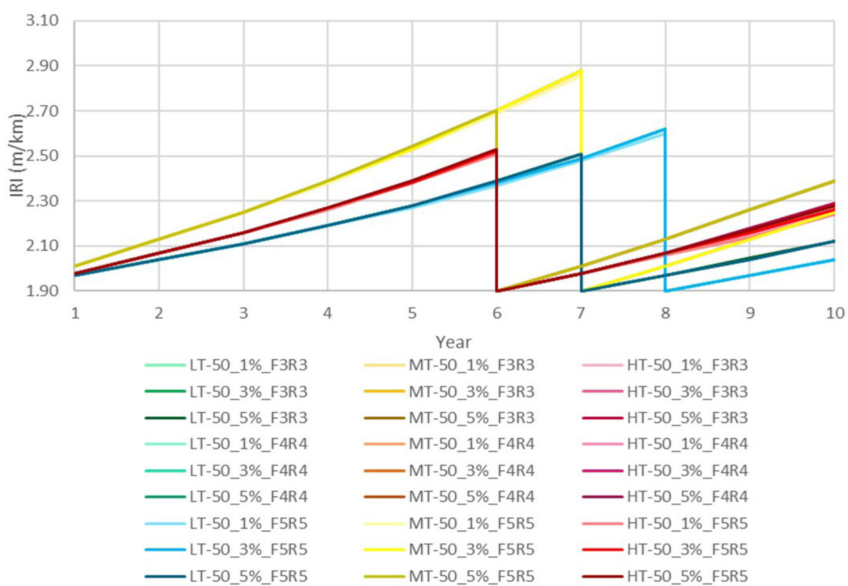

Figure 4. Evolution of IRI for weak subgrade scenarios (CBR=5%).

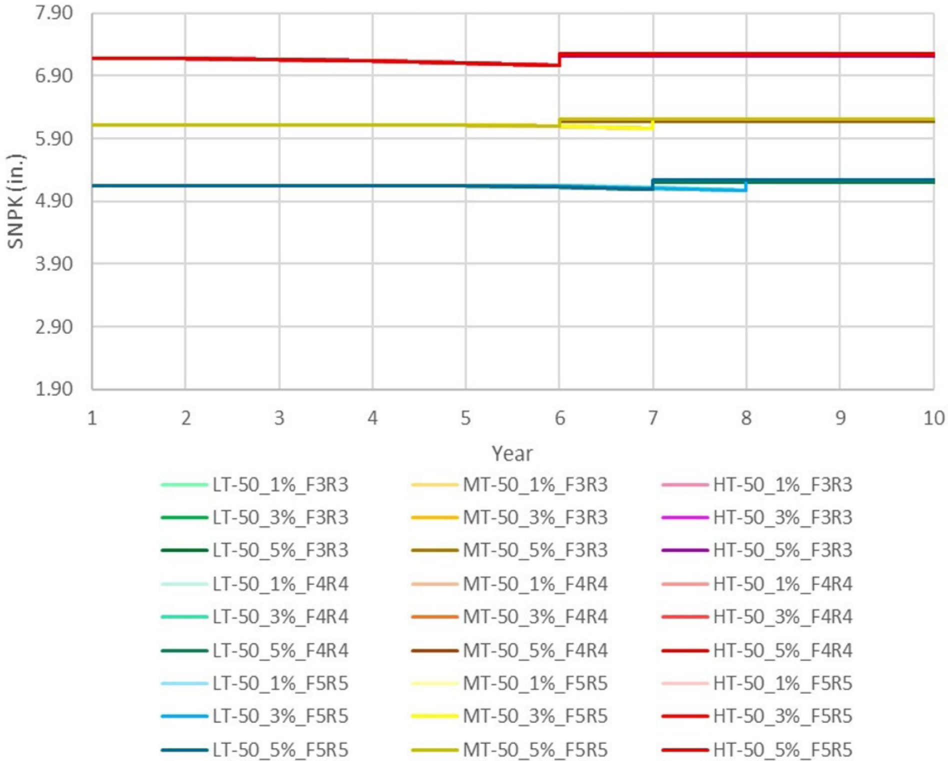

Figure 5. Evolution of SNPK for weak subgrade scenarios (CBR = 5%).

One of the reasons for this inversion phenomenon is due to the effects of water on the structure, which falls under an environmental effect. In the first case, despite the traffic being lower, it is still significant, and the surface layer is directly supported on a granular base where the passage and presence of water are more significant than in the second situation, where the newer surface layer rests on another surface layer, which will also suffer damage and deterioration, although it presents lower permeability than a granular layer.

It is verified in Figures 6 and 7 that the trend of evolution of weak subgrade scenarios, described earlier, is also repeated for medium and strong subgrade situations: three distinct bands of progression of roughness depending on the traffic levels. It is also highlighted the inversion in the medium traffic curves, which show higher IRI values than the high traffic cases, although there is no inversion in the SNPK curve values, as noted in Figure 8 and 9.

Thus, it is perceived that the four variables analyzed here (traffic, annual traffic growth rate, subgrade, and maintenance thickness) present direct influence on the evolution of IRI. The roughness of a highway is an extremely important factor and a concern for users, as it represents the comfort and safety of using that highway.

The evolutions of cracking in the studied cases are presented in the following figures. It is possible to perceive, in Figure 10, that the initiation and progression of the cracked area occur as expected, being more significant for high traffic scenarios and less intense for low traffic cases. From Figure 11, it can be noted that the subgrade influences the cracked area, due to the portion of the adjusted structural number in the cracking model formulation.

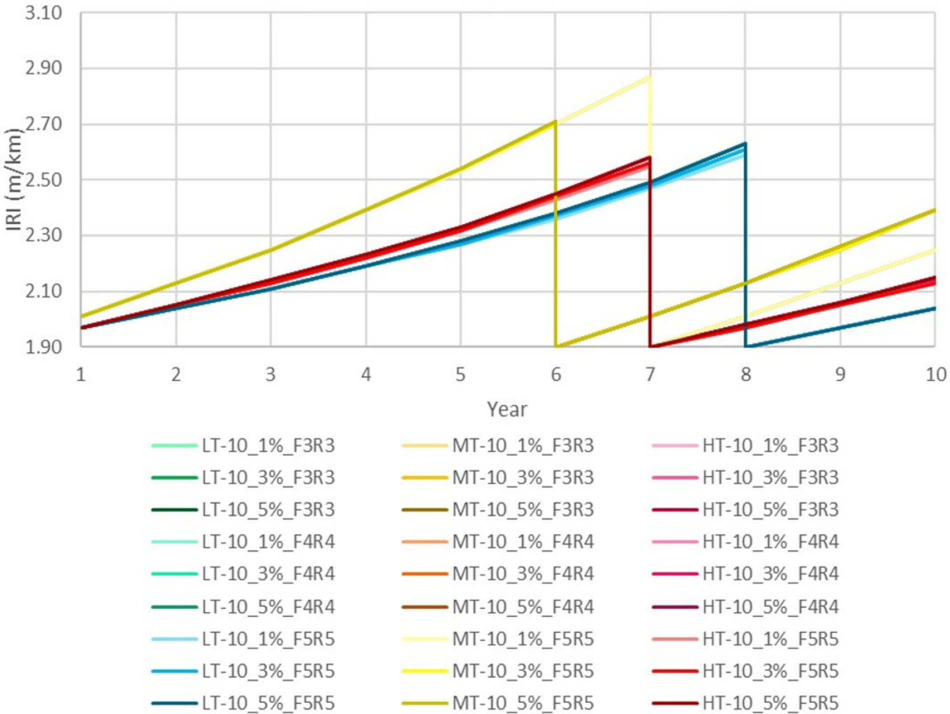

Figure 6. Evolution of IRI for medium subgrade scenarios (CBR = 10%).

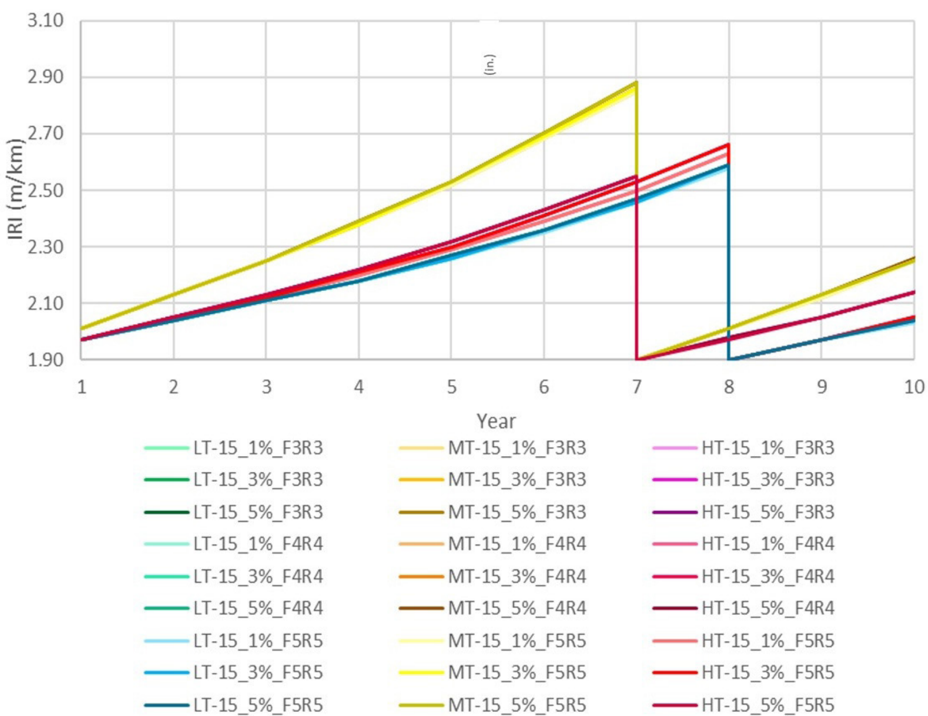

Figure 7. Evolution of IRI for strong subgrade scenarios (CBR = 15%).

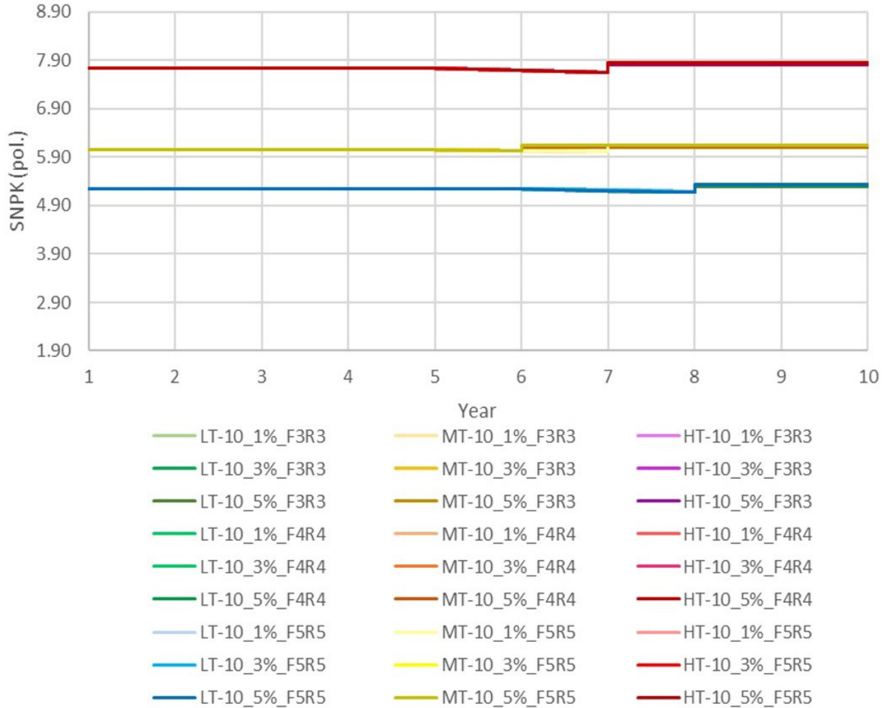

Figure 8. Evolution of SNPK for medium subgrade scenarios (CBR = 10%).

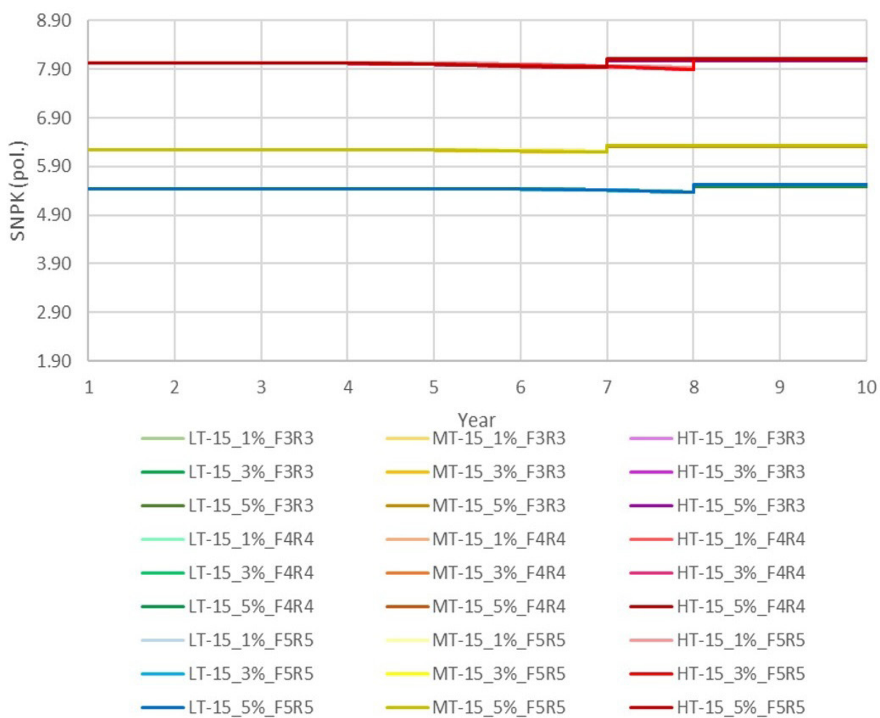

Figure 9. Evolution of SNPK for strong subgrade scenarios (CBR = 15%).

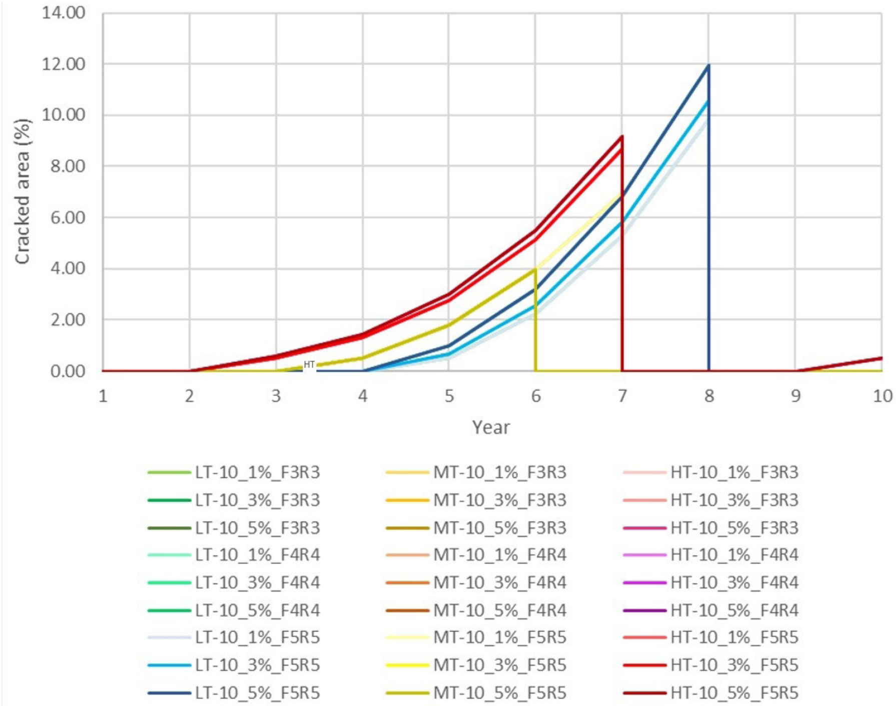

Figure 10. Evolution of cracking for traffic comparison (CBR = 10%).

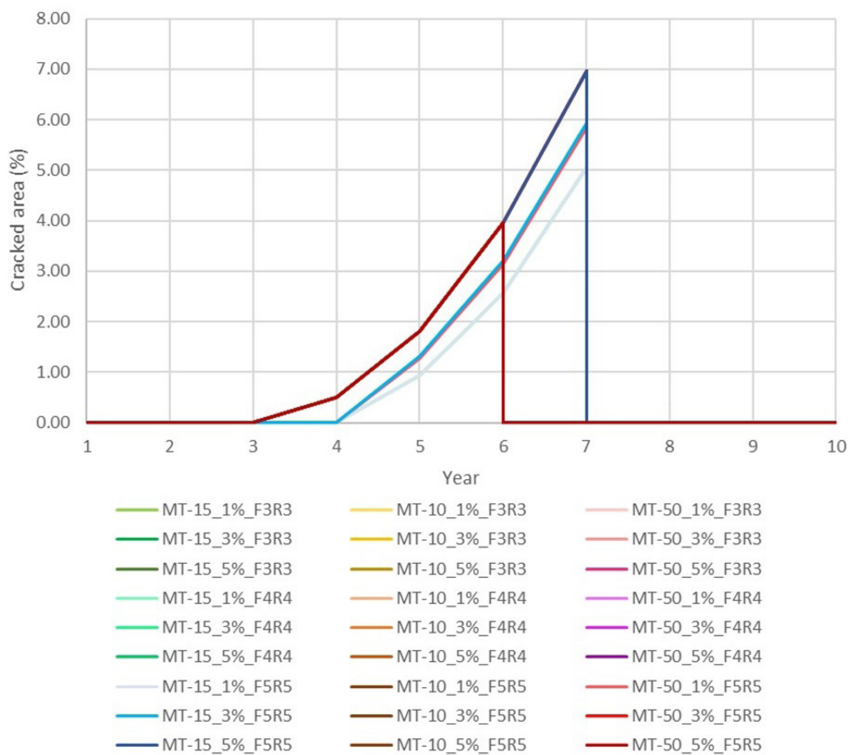

Figure 11. Evolution of cracking for subgrade comparison (medium traffic scenario).

Thus, it is noted that cracking can also be affected by changes in traffic and subgrade. Cracks are common defects in asphalt pavements, and, unlike other defects, their perception by the driver is usually minimal, as their contribution to the quality of the highway and user safety is quite small. However, cracking is a phenomenon that raises concerns due to other factors (Morosiuk, Riley and Odoki, 2004).

Firstly, the appearance of cracks affects the impermeability that the asphalt surface should have, which can result in unwanted water in the other layers of the pavement. Cracking will also directly affect the resistance of the surface layer, reducing its load-bearing capacity and, consequently, that of the underlying layers. Additionally, initial cracks negatively affect the structural integrity of the pavement, leading to other defects such as permanent deformation and pothole formation. Accurate prediction of this cracking allows for optimization of maintenance actions, such as crack sealing and resurfacing, before they evolve into more harmful pathologies (Aggarwal, Jain and Parida, 2003).

3.2. Effects of the New Weight Regulation Law

To analyze the effects of the new 2021 Weight Regulation Law, the roughness parameter was used for the comparison of the two cases (C1 and C2) as it is an indicator of the quality level of highway concession pavements, as defined by the Ministry of Infrastructure (Brasil, 2022). An elevated IRI value indicates a more irregular surface, which can compromise both user comfort and safety, increasing vehicle wear, maintenance needs, and the risk of loss of control (Hood, 2019).

Thus, Tables 5 to 7 indicate the IRI values for the 30th year of the study, the last year of the concession, in which the highway must be delivered with appropriate roughness values. The number of maintenance interventions predicted by HDM-4 for each analyzed scenario over the 30-year study period is also presented. These interventions are included in the schedule whenever the performance limits defined by the PER are exceeded.

Table 6: Summary of final IRI and number of interventions for F4R4 scenarios

Growth rate (%)	Case	LT 15	LT 10	LT 5	MT 15	MT 10	MT 5	HT 15	HT 10	HT 5
		Final IRI - 30th year (m/km)								
1	C1	2.04	2.04	2.04	2.13	2.13	2.13	2.12	2.31	1.90
	C2	2.04	2.04	2.04	2.13	2.25	2.13	2.31	2.42	2.07
3	C1	2.05	2.13	2.13	2.14	2.41	2.27	1.90	2.08	2.34
	C2	2.05	2.13	2.22	2.27	2.41	2.41	2.08	2.09	2.49
5	C1	2.15	2.26	2.37	2.44	2.62	2.61	2.22	2.38	2.62
	C2	2.25	2.37	2.39	2.61	1.90	2.62	2.36	2.39	1.90
		Number of interventions throughout the 30 years of the study								
1	C1	3	3	3	4	4	4	3	3	4
	C2	3	3	3	4	4	4	3	3	4
3	C1	3	3	3	4	4	4	4	4	4
	C2	3	3	3	4	4	4	4	4	4
5	C1	3	3	3	4	4	4	4	4	4
	C2	3	3	3	4	5	4	4	4	5

Table 7: Summary of final IRI and number of interventions for F5R5 scenarios

Growth rate (%)	Case	LT 15	LT 10	LT 5	MT 15	MT 10	MT 5	HT 15	HT 10	HT 5
		Final IRI - 30th year (m/km)								
1	C1	2.04	2.04	2.04	2.12	2.13	2.13	2.12	2.31	1.90
	C2	2.04	2.04	2.04	2.13	2.25	2.13	2.30	2.42	2.07
3	C1	2.05	2.13	2.13	2.13	2.40	2.26	1.90	2.08	2.33
	C2	2.05	2.13	2.22	2.14	2.41	2.40	2.07	2.08	2.47
5	C1	2.15	2.26	2.37	2.44	2.61	2.61	2.22	2.37	2.60
	C2	2.25	2.37	2.39	2.61	2.62	2.62	2.35	2.38	1.90
		Number of interventions throughout the 30 years of the study								
1	C1	3	3	3	4	4	4	3	3	4
	C2	3	3	3	4	4	4	3	3	4
3	C1	3	3	3	4	4	4	4	4	4
	C2	3	3	3	4	4	4	4	4	4
5	C1	3	3	3	4	4	4	4	4	4
	C2	3	3	3	4	4	4	4	4	5

In the cases of low traffic and low growth rate, the increase in vehicle weight had little influence on the pavement, as regardless of the pavement structure, subgrade CBR, and maintenance thickness, the final IRI after 30 years of operation did not show changes, and the number of interventions remained the same. However, analyzing the year-by-year roughness values of the two cases, it is possible to verify that there is an increase in the evolution of roughness for all scenarios when there is a tolerance of 12.5% per axle, indicating that despite the effects of these overloads not

Table 5: Summary of final IRI and number of interventions for F3R3 scenarios

Growth rate (%)	Case	LT 15	LT 10	LT 5	MT 15	MT 10	MT 5	HT 15	HT 10	HT 5
		Final IRI - 30th year (m/km)								
1	C1	2.04	2.04	2.04	2.13	2.13	2.13	2.21	2.31	1.98
	C2	2.04	2.04	2.04	2.13	2.25	2.13	2.31	2.43	2.07
3	C1	2.05	2.13	2.14	2.14	2.41	2.27	1.90	2.08	2.36
	C2	2.13	2.14	2.22	2.27	2.57	2.41	2.08	2.09	1.90
5	C1	2.16	2.27	2.38	2.45	2.62	2.62	2.37	1.90	2.03
	C2	2.26	2.39	2.40	2.62	1.90	2.63	1.90	1.90	2.18
		Number of interventions throughout the 30 years of the study								
1	C1	3	3	3	4	4	4	3	3	4
	C2	3	3	3	4	4	4	3	3	4
3	C1	3	3	3	4	4	4	4	4	4
	C2	3	3	3	4	4	4	4	4	5
5	C1	3	3	3	4	4	4	4	5	5
	C2	3	3	3	4	5	4	5	5	5

being evident in the final IRI parameters and the number of interventions, they will increase over the years with the acceleration of the roughness evolution.

For medium and high traffic cases, the variation in roughness was more noticeable, with changes in the final IRI for the C2 cases. In addition to the change in roughness, the high traffic cases also showed an increase in the number of interventions over the 30-year study period, indicating the need to increase the expected cost for this period. It is important to highlight that the only scenarios where the C2 case presented lower final IRI values than the C1 case were under conditions where more interventions were needed over the 30 years, and therefore, the reduction in roughness at the end of the analyzed period.

Finally, it is possible to highlight that the variation in roughness and number of interventions was less noticeable for scenarios where maintenance had a greater thickness, i.e., for the cases of milling 5.0 cm and overlay of the same 5.0 cm (F5R5). Therefore, the effect on the pavement that the new weight regulation law may cause can be compensated with more robust maintenance interventions, thus avoiding that the overload not foreseen in the project affects the lower layers of the structure, causing higher future maintenance costs.

4. CONCESSION FEASIBILITY ANALYSIS

4.1. Economic feasibility

Based on the maintenance interventions predicted by HDM-4 over the 30-year concession period, a preliminary economic analysis was conducted to estimate the financial impact of maintenance under different scenarios. Average unit costs for milling and overlay interventions were used, based on the Unit Price Table (*Tabela de Preços Unitários* - TPU) from the DER as of January (DER, 2025). For the calculation of each intervention cost, it was assumed that maintenance would be carried out across the full 7-meter-wide lane and over a 1 km stretch, thus obtaining the intervention cost per kilometer of road. Table 8 presents the unit and per-kilometer costs for each type of intervention studied.

Based on the number of interventions predicted in the different scenarios presented in this study, it is possible to observe that in the most critical cases (medium to high traffic and high growth rate), the increase in axle overload from 10% (Case C1) to 12.5% (Case C2) resulted in an increase from 3 to 4 interventions over the 30-year analysis period. Therefore, Table 8 also presents the costs for 3 and 4 interventions per type of maintenance.

Table 8: Summary of intervention costs

Maintenance	Unit cost (R$)	Kilometer cost (R$/km)	Cost of 4 interventions (R$/km)	Cost of 5 interventions (R$/km)	Increase in Costs	
					(R$/km)	(%)
F3R3	63.00	440,996.50	1,763,986.00	2,204,982.50	440,996.50	25%
F4R4	82.57	577,962.00	2,311,848.00	2,889,810.00	577,962.00	25%
F5R5	102.13	714,927.50	2,859,710.00	3,574,637.50	714,927.50	25%

As shown in Table 8, it is evident that an increase in axle overload from 10% to 12.5%, as permitted by the new 2021 Weight Regulation Law, may result in a significant cost increase, representing a 25% rise in maintenance costs per kilometer. Projecting these values onto a theoretical 100 km stretch, the impact of this legislative change in Brazil could result in an increase of up to BRL 71.5 million in maintenance costs for the F5R5 maintenance scenario alone over the contract period.

Conversely, the study also suggests that choosing more robust interventions, such as the F5R5 maintenance type, although more expensive per unit, tends to reduce the frequency of maintenance and better preserve the final IRI, which may balance costs over time and keep the pavement in adequate condition for a longer period.

4.2. Operational and management feasibility

In addition to the economic analysis, it is important to consider the operational and managerial challenges arising from scenarios with increased frequency of interventions throughout the concession period. The increase in maintenance frequency, especially on highways with heavy traffic and low-quality subgrade, may compromise road availability, generating impacts on traffic flow, user comfort, and operational safety.

From a contractual management perspective, a higher frequency of interventions requires enhanced technical and logistical capacity from the concessionaire, including detailed planning of works, efficient scheduling, and timely availability of material and human resources. Additionally, operations involving multiple intervention events may increase indirect costs associated with signage, detours, inspections, and communication with users. These factors, although not always directly quantified in techno-economic models, significantly influence the perception of service quality and the sustainability of the contract.

Therefore, considering the results of this study, it is essential to recognize that the feasibility of highway concessions is linked not only to direct maintenance costs but also to the operators' ability to deal with the operational and managerial challenges arising from increased pavement deterioration.

5. CONCLUSIONS

This study aimed to understand the influence of traffic on the performance of flexible pavements for Brazilian highway concessions using the performance prediction models of the HDM-4 program. Based on the research, it can be concluded that traffic exerts a significant influence on the durability of pavement design and is directly related to the necessary maintenance services required to ensure adequate levels of comfort and safety throughout the concession period. It was also possible to observe the effects that variations in traffic levels, annual growth rates, and subgrade bearing capacity can have on the evolution of performance parameters over the 30-year concession period.

When analyzing the evolution of longitudinal roughness, it was found that traffic levels, determined by AADT, had a greater influence on the evolution of IRI than annual growth rates, and that subgrade variation influenced longitudinal roughness, although more noticeably in cases of higher traffic. In addition, it was observed that different milling thicknesses influenced the evolution of the parameter, especially after halfway through the analyzed period, due to the configuration adopted in this study, which always aimed to achieve an IRI of 1.90 m/km after maintenance. In the study of cracking, it was also possible to verify that both variables studied, traffic and subgrade, have a direct and significant influence on the evolution of the cracked area in the pavement throughout the entire design period.

It was also observed that the 2021 change in Brazilian legislation, which allowed an increase in axle overload from 10% to 12.5%, may have the potential to impact pavement quality and reduce its service life, suggesting possible effects on the investments planned for maintenance activities before the implementation of the new Weight Regulation Law. However, it was concluded that these negative effects due to higher overloads not accounted for in the design can be minimized, or even offset, with more robust maintenance thicknesses.

Finally, from the inclusion of a preliminary economic analysis, it was possible to identify that the overload permitted by Law No. 14.229/2021 may represent increases of up to 25% in maintenance costs on high-traffic sections. This increase has the potential to compromise the financial sustainability of the contracts, requiring rebalancing or tariff increases, especially in projects whose design assumptions do not include these new legal limits. Thus, it becomes essential that regulatory agencies, concessionaires, and designers consider these variables in the planning and economic-financial modeling of future concessions, ensuring not only the technical performance of road assets but also the operational and economic viability of the contracts.

It should be emphasized that, beyond economic aspects, the different strategies analyzed must consider, even if qualitatively, the inconveniences and disturbances faced by users. This includes delays in travel times due to waiting and potential traffic congestion related to lane closures and interruptions in traffic flow for the execution of works. The greater the frequency and number of interventions over time, the higher the costs for users due to increased fuel consumption, as well as factors such as discomfort and increased likelihood of traffic accidents. On the other hand, less frequent and more spaced-out interventions tend to minimize these impacts, benefiting users and overall mobility.

Moreover, it is important to highlight a possible inconsistency between current legal requirements and modern pavement design and evaluation methods, such as HDM-4. While technical models consider detailed structural parameters and performance-based simulations over time, Brazilian legislation still uses fixed axle load limits and tolerances based on weighing equipment error margins, often without considering the cumulative impacts of these overloads on pavement structure. This lack of alignment may compromise the effectiveness of planning and management tools, particularly in older projects that did not account for such excesses. Therefore, it is crucial that legal standards be updated in line with the latest technical methodologies, ensuring greater coherence between what is planned in design and what is permitted in operation within highway concessions.

It is worth noting that the chosen methodology has certain limitations, as it is a parametric study calibrated based on a relatively limited sample of Brazilian highways, which may require revisions and updates to expand its applicability. Future studies may expand the approach adopted, adding cost evaluation and validating the methodology under different environmental and climatic conditions, which would contribute to proving its applicability in an even broader range of scenarios. Additionally, it is recommended that subsequent research use empirical data from existing contracts and comprehensive economic feasibility assessments from National Land Transport Agency (*Agência Nacional de Transportes Terrestres* – ANTT) monitored concessionaires to validate and substantiate the results obtained in this study, strengthening the reliability of the proposed methodology and reinforcing the integration between technical performance and contractual sustainability.

AUTHORS' CONTRIBUTIONS

TCMP: Methodology, Resources, Investigation, Data Curation, Writing, Software, Visualization; CYS: Data Curation, Supervision, Formal Analysis, Validation.

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.

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