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Mechanistic-empirical assessment of axle load legal limits on Brazilian roadways

Avaliação mecanístico-empírica dos limites legais de carga por eixo em rodovias brasileiras

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ABSTRACT

This paper presents a comprehensive mechanistic-empirical assessment of axle load legal limits policy on Brazilian roadways, considering the intricate balance between enhanced freight transportation and potential pavement deterioration. Focusing on the prevailing flexible pavements, the study explores factors such as asphalt concrete stiffness, thickness, and axle-load increments, accounting for variations in tire-load and pressure. The analysis reveals complex relationships between these factors and their impact on pavement distress mechanisms, particularly fatigue cracking and rutting. The investigation highlights the substantial influence of axle load legal limits adjustments, even seemingly minor ones, on pavement damage, ride quality, safety, and operational efficiency. A calibrated model for assessing mechanistic-empirical load equivalency factors (LEFs) was developed, offering insights into the disparities between the model and existing empirical equations used in the Brazilian Pavement Design Guide (BPDG). This comparison underscores the potential underestimation of axle load legal limits adjustments in the current approach, emphasizing the importance of informed decision-making in transportation policy. In conclusion, this study provides critical insights for policymakers and engineers while considering axle load policy adjustments. The findings emphasize the significance of accurate engineering considerations to sustainably balance economic growth, road safety, and efficient freight transportation within Brazil's evolving road network.

RESUMO

Este trabalho apresenta uma avaliação empírico-mecanística dos limites legais de carga por eixo nas rodovias brasileiras, considerando o equilíbrio entre o frete rodoviário e o controle da deterioração do pavimento. Com ênfase em pavimentos flexíveis, o presente o estudo explora fatores como a rigidez do concreto asfáltico, espessura e incrementos de carga por eixo, variações na carga por eixo e pressão dos pneus no desempenho de pavimentos. A análise demonstra como são complexas as relações entre esses fatores e o impacto nos mecanismos de deterioração do pavimento, particularmente em termos de trincas por fadiga e deformação permanente na trilha de roda. O estudo também aborda como o aumento nos limites legais de carga por eixo impactam a capacidade do pavimento em servir ao usuário com segurança e eficiência operacional. No estudo é calibrado um modelo para estimar os fatores de equivalência de carga empírico-mecanístico (FEC), comparando as disparidades dos resultados obtidos com as equações empíricas utilizadas no Guia de Projeto de Pavimentos Brasileiros (GPPB). Os resultados indicam como os ajustes nos limites legais de carga por eixo são subestimados no atual método de dimensionamento de pavimentos, enfatizado como o emprego de ferramentas de engenharia podem impactar, de forma sustentável, o crescimento econômico, a segurança dos usuários e um eficiente transporte de cargas na malha rodoviária brasileira.

1. INTRODUCTION

The road transportation mode offers great operational versatility attributed to its speed and high accessibility. However, it has limitations on the volume and weight transported, which can result in high costs for long-distance freight and early deterioration in segments without the proper weight-load control. The demand of road freight is naturally stimulated by the country's economic development. Thus, the willing for increasing the pay-load is govern by the assumption of increased service levels resulting from the reduction in the traffic needed to transport the same amount of goods and the economic profit on reduced travels. Nonetheless, previous studies have proven that higher loads significantly contribute to the deterioration of pavements, compromising traffic comfort and safety, as well as increasing vehicle operation costs (Fernandes Jr., 1994).

In October 2021, the National Congress of Brazil approved the House Bill No. 1050, which increased the weight limit per axle from 10% to 12.5% (CONTRAN, 2021). Despite the adjustment being only 2.5%, the Brazilian Pavement Design Guide (BPDG) does not factor in overweight tolerances, which explains why most of the highways - typically designed for a medium-term horizon of 10 years - have been experiencing premature structural failure. Furthermore, the asphalt concrete layer utilized on Brazilian highways possesses an average thickness that is one-third of the surface layer thickness used in countries where asphalt mixture design methods were established, resulting in greater levels of stresses and strains, compromising the pavement performance (Gonçalves, 2018).

Therefore, an evaluation of the new axle load legal limits adjustment is necessary, using more updated engineering concepts that consider the relative damage based on the structural capacity of pavement layers, tire inflation pressure (assumed to be equal to tire-pavement contact pressure), and the main failure criteria observed on Brazilian highways.

2. LOAD EQUIVALENCY FACTOR

The Load Equivalency Factors (LEFs) are critical in pavement design because they convert mixed-axle loads to a single-design axle load, usually referred as standard-axle load. Conceptually, the LEF represents the ratio between the number of repetitions of a given axle load and of a standardized axle load (generally 18-kip single-axle), representing the relative damage or reduction of pavement performance. Thus, the LEF for a given axle is a complex function of many variables, including axle weight (or tire load), pavement support capacity, and a failure criterion.

In the 1950s, the largest real-scale road experiment, known as the AASHO Road Test, was conducted to better understand the loads applied to pavements and how the main failure mechanisms develop (HRB, 1962). A significant outcome of this experiment was an empirical based LEF with an exponential relationship between axle load and pavement damage, with the exponent ranging between three and five, but conventionally set at four and referred to as the "Fourth Power Law".

The LEFs can also be originated from theoretical concepts based on pavement mechanics, being referred to as *mechanistic based*. However, LEF are not purely empirical, since they require statistical adjustments based on consistent analytical theories, nor are they solely mechanistic, as they require experimental validation. Hence, a better understanding of LEFs is achieved through a *mechanistic-empirical* approach.

Pavement performance models generally consider the number of cycles for a specific failure mechanism, as a function of only one structural response (δ), as shown in Equation 1.

$$N = a \cdot \left(\frac{1}{\delta}\right)^{b} \tag{1}$$

where N is the number of load applications, a and b are respectively coefficients and exponents associated with the failure criteria, calibrated experimentally. By combining the Equation 1 with the concept of LEF, it is possible to express then a *mechanistic-empirical* equivalence through the ratio between the structural responses produced by any axle load (δ_i) and those produced by a standard-axle load (δ_s), as shown in Equation 2.

$$LEF_{i,s} = \frac{N_s}{N_i} = \frac{a \cdot \left(\frac{1}{\delta_s}\right)^{b}}{a \cdot \left(\frac{1}{\delta_i}\right)^{b}} = \left(\frac{\delta_i}{\delta_s}\right)^{b} \tag{2}$$

To validate Equation 2, a calibration of the exponent b would be necessary. Otherwise, this relationship would be limited to the mechanistic theoretical framework.

Since some pavements during the aforementioned AASHO Road Test did not reach the failure threshold considered at the time, it was believed that the empirical LEFs underestimated the service life of thicker pavements. Small, Winston and Evans (1989) reviewed the data through a survival analysis including those pavements that never failed and found an exponent b closer to 3. Irick (1989), a statistician that took part of AASHO Road Test, reconducted the LEF analyses using the same field data but incorporating the updated knowledge on pavement distress at the time and also found a coefficient closer to 2.5 for both flexible and rigid pavements (except when considering the pumping in concrete slabs, whose value approached 4). Thus, in the context of this analysis and to better to assess impact of the axle load limits adjustment in terms of LEF on Brazilian highways, the exponent for the *mechanistic-empirical* LEF was generalized according to the "Fourth Power Law" ($b=4$ in Equation 2).

The conservative choice is justified by the fact that the vehicles used in the AASHO Road Test were considerably different from those currently used in Brazil, especially in terms of tire type, tire inflation pressure, suspension type, and axle loads. Additionally, pavement performance thresholds during the AASHO Road Test were assessed in terms of the Serviceability Index, while in Brazil the fatigue cracking is the prominent structural failure distress.

3. FACTORIAL EXPERIMENT

In a mechanistic-empirical pavement analysis, fundamental pavement structural responses under repeated traffic loadings are calculated using a multi-layer linear elastic approach, assuming that a flexible pavement is a multi-layered structure and that each layer exhibits a linearly elastic response to traffic loads. According to Prozzi et al. (2022), although this is not exactly the case for a real structure, the linearity assumption is reasonable at the low strain levels, typical of highway traffic.

For this study, the Elastic Layered System Model 5 (ELSYM5) software was used to compute the pavement structural responses. The ELSYM5 assumes that each layer is composed of homogeneous, isotropic, weightless, and linearly elastic material. The layered system's surface is free of shear forces, where each layer has uniform thickness and extends infinitely in the horizontal direction. Also, there is continuity between the layers (i.e., perfectly frictional or rough interfaces) and the bottom layer can be semi-infinite or supported by a rigid base (Fernandes Jr., 1994).

The analysis was exclusively conducted within the realm of flexible pavements, as they constitute the predominant pavement type across Brazilian highways. Furthermore, simulating semirigid pavements on linear-elastic software presents complexities, owing to the fact that the progression of fatigue cracking from bottom to top only occurs after the cemented base layer, possessing rigidity and tensile strength, has been compromised.

All flexible structures considered were with both granular base, subbase and subgrade, with resilient modulus of 50, 35 and 10 ksi, respectively. The proposed factors and it respective levels are summarized in Table 1.

Table 1. Factor levels for the mechanistic-empirical LEF.

Factor	Level
AC Stiffness	600, 900, 1200 and 1500 ksi
AC Thickness	2, 4 and 6 inches
Axle-load Increment	0.0*, 2.5, 5.0, 7.5, 10.0 and 12.5%

*The 0.0% increment represents the standard-axle load with 18-kip and 80 psi.

To better account for the effect of the structure, the asphalt concrete (AC) stiffness was disaggregated into four levels, based upon technical literature. For the AC thickness, three levels were considered ranging from the most common (2 inches) to the maximum single layer thickness allowed by the BPDG (6 inches). The axle-load increments were based on the standard-axle load (single axle, dual wheels with 18-kip and 80 psi) and evenly divided in intervals from 2.5 up to 12.5 percent increment, according to the weight limits adjustment policies. Furthermore, the axle-loads were associated with different tire inflation pressure levels, evenly distributed from 90 to 130 psi.

The structural response locations analyzed in the software routine were based on the two main structural failure mechanisms: *fatigue cracking* and *rutting*. Fatigue cracking is a load related distress on cemented layers (either by Portland cement or asphalt binder) that usually occurs at stress levels lower than the critical maximum (Roberts et al., 1991). Transfer functions for fatigue cracking are generally as proposed by Monismith and Deacon (1969), where the fatigue failure starts after a certain number of load repetitions which is function of a critical tensile strain at the bottom of the asphalt layer (ε_{ht}).

Rutting is a distress associated with the consolidation and shear resistance of the pavement layers under repeated loads, resulting in wheel path depressions with small lateral pavement elevations (Bairgi, Manna and Tarefder, 2019). While measuring the rutting itself on the field is a straightforward task, predicting it can be quite complex because it involves not only material characterization, but also environmental conditions as well as asphalt binder aging (Medina and Motta, 2015). Its evaluation in pavement structures often relies on controlling the vertical strain at the top of the subgrade (ε_{vc}), a metric first introduced by researchers from SHELL, prioritizing the overall rut instead of computing the contribution of each individual layers, as per the principles of viscoelastic theory, once the latter approach requires more extensive material properties and there is lack of well-documented field experiments (Fernandes Jr, 1994). During the AASHO Road Test, the total rutting measurements occurred manly in both asphalt (32%) and sub-base (45%) layers, with a much smaller contribution from the base (14%) and subgrade (9%) layers (HRB, 1962).

Pavement rutting consists of two parts: a recoverable deformation (resilient) and non-recoverable deformations (plastic). Current design practices prioritize resilient behavior, overlooking the plastic behavior of pavement materials, which results in most rut prediction models considering layered vertical strain on pavements. Few researchers hypothesized and demonstrated that the applicability of shear strain in the asphalt layer is a more relevant approach for asphalt mixtures rut prediction (Singh and Sahoo, 2021). However, it would then require specific analysis for the remaining unbounded layers.

Thus, in this study the vertical compression strain at the top of the subgrade was used as the rutting control parameter for the whole pavement structure.

4. RESULTS AND DISCUSSIONS

Since the structural responses come straightforward from the linear-elastic software ELSYM5, there was no variability on the data for the proposed scenarios. In order to assess the effect of each factor, the variation on the LEF for the two major distresses (fatigue cracking and rutting) was considered as function of only one factor at time, while the remaining were considered replicates of the same factor.

4.1. Impact of weight limits adjustment on pavements

As aforementioned, the LEF were calculated considering the structural responses from the standard-axle (18-kip and 80 psi) as the reference in each factor combination. In Figure 1 it is presented the effect of different asphalt concrete (AC) thickness while considering the load spectrum from 0 up to 12.5% increment in the axle load. Clearly the LEF variability increased towards the thinner asphalt thickness, reaching extreme values due to the combination of high tire pressure at maximum axle load. It is clear how well-behaved thicker pavements (from 4 to 6 inches) reduced the horizontal tensile strains all other conditions remained unchanged.

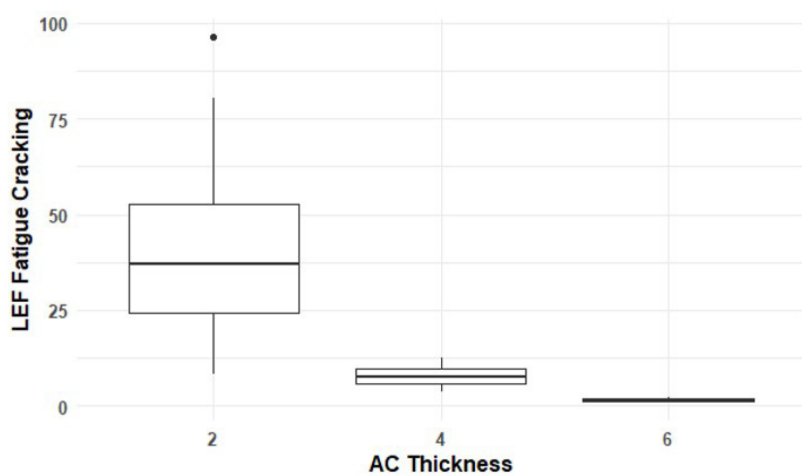


Figure 1. LEF for fatigue cracking based on AC thickness.

When considering the effect of the AC stiffness (Figure 2), the median LEF based on fatigue cracking for all proposed stiffness were close enough to each other. However, its variability through all the resilient modulus range exhibited extreme values for the higher cap (1,500 ksi) due to the critical structural responses concentrated within the asphalt layer, and when combining low thicknesses with high axle loads. As the asphalt layer stiffness increases, it becomes more brittle, leading to concentrated state of stress and changes on its relaxation behavior. This, in turn, has a detrimental effect on the pavement ability to withstand fatigue cracking.

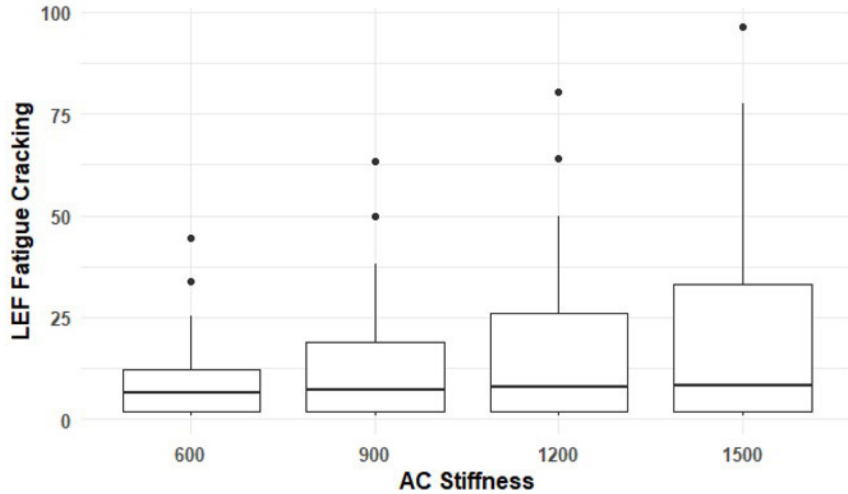


Figure 2. LEF for fatigue cracking based on AC stiffness.

In Figure 3 is presented the axle load increment from 0% (standard-axle) up to 12.5% (new axle weight limit adjustment proposed), in terms of tire-load, which is already combining different tire pressure levels (starting with 80 psi up to 130 psi). The axle weight increment effect on the LEF values was the most notorious, even considering different thickness and stiffness values, which impact directly on the variability for each loading level. When considering the effect upon the standard axle, the new weight limit represented at more than twice the damage to the pavement, with extreme values changing its order of magnitude (LEF ranged from 10 to close to 100). In practical terms, when using fatigue cracking as the criterion for failure, surpassing the previously axle weight limit policy of 10% increment has proven sufficient to significantly reduce the time needed for pavement maintenance and rehabilitation services by approximately half. This has also led to a drastic decrease in pavement ride quality (increasing it roughness), which impacts back on the roadway operational costs (a substantial portion of roadway maintenance expenses) and safety.

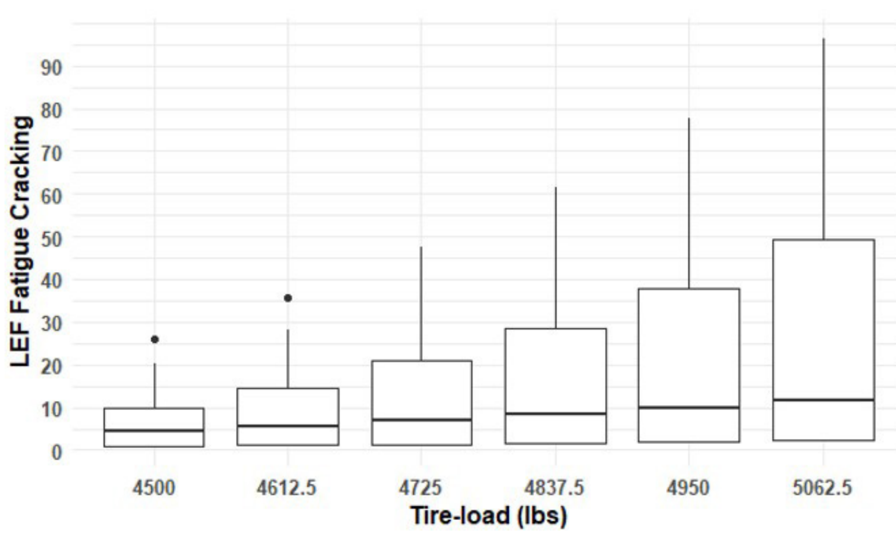


Figure 3. LEF for fatigue cracking considering each tire load and pressure increment based on axle-weight limit policy history.

As observed while considering fatigue cracking, when assessing pavement rutting by the vertical strain at the top of the subgrade, the LEF values were also sensitive to the asphalt layer thickness. In Figure 4 the LEF is presented as a function of the AC thicknesses, which showed and increasing variability towards thinner asphalt courses, and extreme LEF values due to the combination of high tire pressures (130 psi) and axle loads (12.5%).

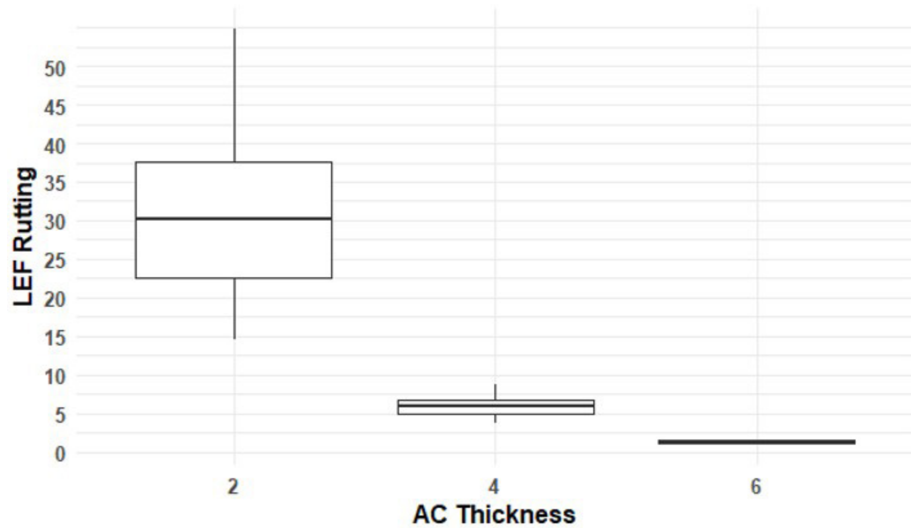


Figure 4. LEF for rutting based on AC thickness.

In Figure 5 is depicted the impact of asphalt concrete stiffness on rutting. The observed variability closely mirrors the behavior exhibit while evaluating fatigue cracking, albeit with less extreme values. This trend is attributed to the stress reduction on lower layers due to the stiffness increase on upper layers, which resulted in values with approximately half the magnitude (from 100ths to 50ths).

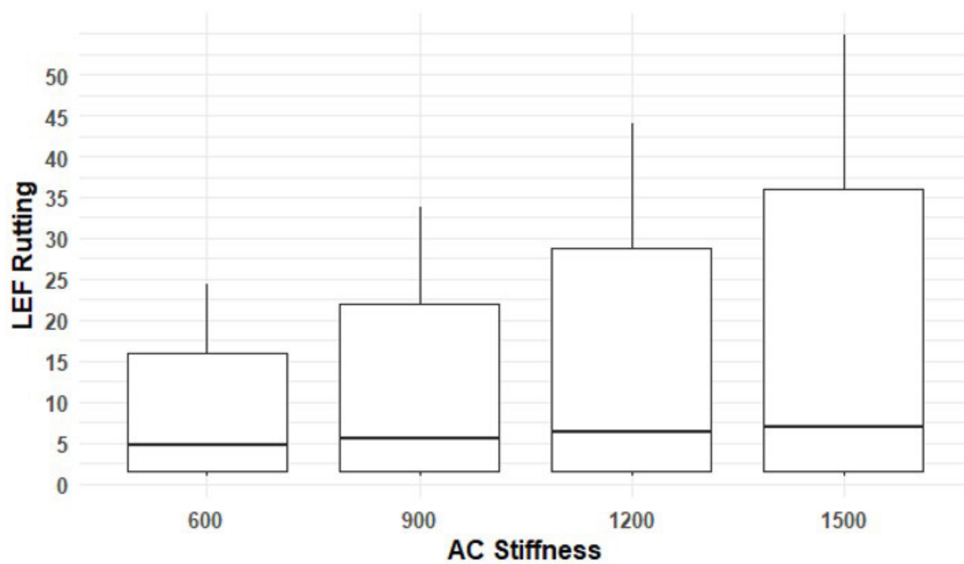


Figure 5. LEF for rutting based on AC stiffness.

Lastly, in Figure 6 is depicted the variation of the LEF due to the incremental increase in axle weight. Similar to the findings for the fatigue cracking criterion, there is a notable rise in LEF values for rutting, posing implications for maintenance and operational costs. With a 12.5% adjustment to weight limits, the median damage to the pavement structure due to rutting was observed to exceed 100% the standard axle, exhibiting high variability and extreme values, particularly when combining low thicknesses and high tire pressures. Consequently, to justify maintaining current weight limits, the economic benefits of transporting overweighted axles must yield a surplus that enables proper maintenance and rehabilitation, without disproportionately burdening users through operational costs. Furthermore, the prior axle weight tolerance (10%) alone was sufficient to generate a median LEF twice as high as that considered during pavement design routines in Brazil that don't consider any axle load increment.

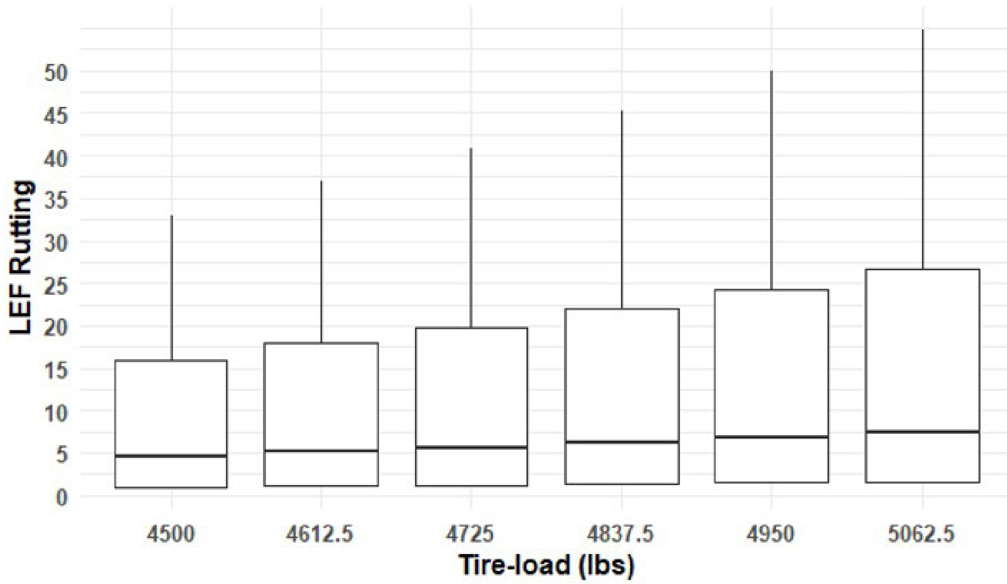


Figure 6. LEF for rutting considering each tire-load and pressure increment based on axle-weight limit policy history.

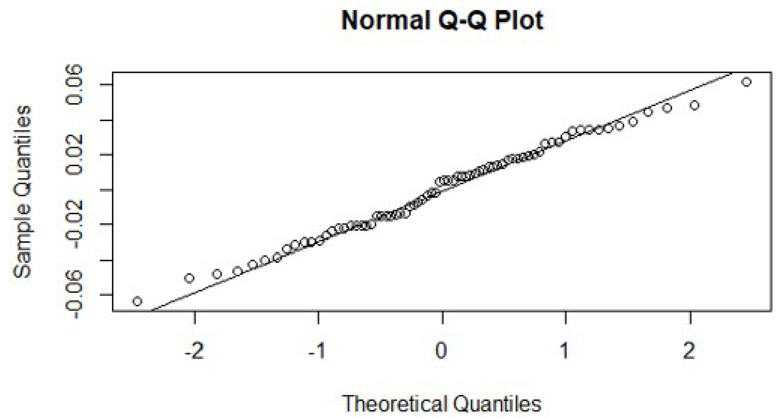
4.2. Modeling LEF on fatigue cracking for single axles

All the routine done on ELSYM5 was based on increment over the standard-axle, which is a single axle with dual wheels. Hence, using the structural responses and combining with the factors considered, it was possible to calibrate a model for single-axles with dual wheels to assess the LEF for any given thickness, stiffness and axle-load (expressed in terms of tire-load). It is important to notice that the tire pressure was directly associated with the tire load during the software routine, being implicit on the results obtained in terms of LEF.

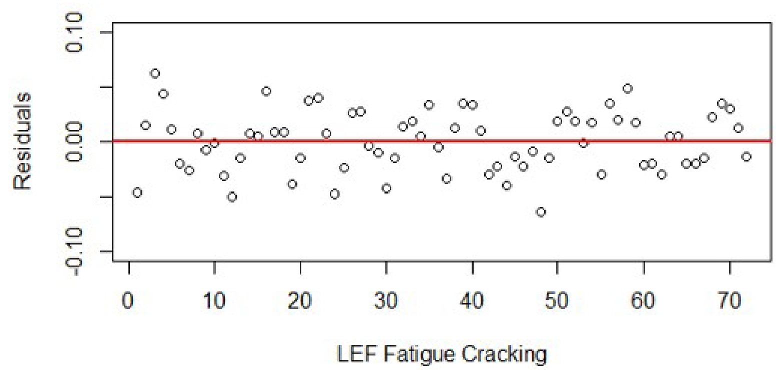
The model chosen for fatigue cracking as the failure criterion, the most critical on Brazilian roadways, considered the interaction between the aforementioned factors, as shown in Equation 3.

$$\log(\mathrm{LEF}) = \beta 1 + \beta 2 * \log(t) + \beta 3 * \log(E_{asphalt}) + \beta 4 * \log(L) + \beta 5 * \log(t) * \log(E_{asphalt}) + \beta 6 * \log(t) * \log(L) + \beta 7 * \log(E_{asphalt}) * \log(L) + \beta 8 * \log(t) * \log(E_{asphalt}) * \log(L) \tag{3}$$

where β correspond to each respective linear regression coefficient, t is the thickness of the respective pavement structure, $E_{asphalt}$ is the resilient modulus for the asphalt concrete layer and is the tire-load. The model had a R-squared of 0.9957 and an adjusted R-squared of 0.9952. The linear regression assumptions were verified and presented in Figure 7. The calibrated coefficients for each factor are presented in Table 2.



(a)



(b)

Figure 7. Verifying model residuals: (a) normality and (b) homoscedasticity.

Table 2. Coefficients calibrated for the model.

Parameter	Coefficient	t-stat	p-value
β1	-411.12	-9.47	0.00
β2	178.48	5.62	0.00
β3	39.78	6.33	0.00
β4	48.91	9.54	0.00
β5	-19.00	-4.13	0.00
β6	-21.23	-5.67	0.00
β7	-4.73	-6.38	0.00
β8	2.26	4.17	0.00

As already mentioned, the BPDG doesn't not considered on its routine the weight limits adjustment proposed on past Bills from the Congress. In the current Brazilian method, the LEF is calculated based on empirical equations calibrated from the United States Corps of Engineers (USACE) and the American Association of State Highway and Transportation Officials (AASHTO), which don't consider, not even indirectly, the pavement structure contribution on the LEF and, therefore, can underestimate the effect of weight limits adjustments. Using the model calibrated (Equation 3) for a 6-inch thick pavement with 600 ksi resilient modulus, a comparison on the LEF was made with the current equations from the BPDG method, considering a single-axle load with the new weight limit adjustment of 12.5%, as shown in Table 3. The LEF obtained was 145% greater than the highest value from the empirical equations from the BPFD method.

Table 3. LEFs comparison.

Description	Tire-load (lbs)	LEF		
		MODEL	USACE	AASHTO
Single axle (+12.5%)	6,195	8.1	3.3	2.4

To better assess other axle configurations, it would be necessary to repeat the linear-elastic software routine, considering the influence additional tire-loads to represent the case of tandem and tridem group axles. Furthermore, specific models would be then calibrated for each case, to capture the cumulative stress and strains produce by the additional axle group loads.

5. CONCLUSION

In the context of the growing demand for road freight transportation in Brazil and the recent adjustment of axle load legal limits, this paper embarked on a comprehensive mechanistic-empirical assessment of the impact of these adjustments on the structural integrity of flexible pavements and it has shed light on the critical considerations that need to be addressed when contemplating changes to axle load legal limits. The study focused on flexible pavements and evaluated factors such as asphalt concrete stiffness, thickness, and weight limits adjustments, in terms of variation in tire-load and pressure.

The findings underscored the nuanced impact of these factors on the overall LEFs, that can have profound consequences for road maintenance cost. The analysis demonstrated that even seemingly minor adjustments in weight limits, such as the recent 2.5% increase in axle weight limit, can yield substantial increases in pavement damage, once the overall increment would be of 12.5%.

This study also calibrated a LEF model for assessing fatigue cracking due to single-axle loads in a network-level basis. By comparing the outcomes of this model with the existing empirical equations used in the Brazilian Pavement Design Guide (BPDG), the paper highlighted significant disparities. The model revealed that the BPDG's current approach may significantly underestimate the impact of weight limit adjustments, that can be 145% greater than what is considered on the method, potentially leading to inadequate design and maintenance strategies, as well as premature deterioration of roadways. All the analysis were performed within assumption such as the linear-elasticity of stress propagation, which is the typical approach for highway loads, but it did not account for in-service pavement and aging factors, that also play an important rule in pavement performance.

In conclusion, this paper shown the critical importance of conducting comprehensive mechanistic-empirical assessments when contemplating changes to weight limits on roadways in a policy level, and use statistical tools to assess trends in the load equivalency factor given the primary factors for pavement design in a network-level. The study provided insights into the complex relationships between factors affecting pavement distress, offering enough evidence for reviewing decision-making in the Brazilian weight policy for freight.

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