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Load equivalency factors for off-road trucks

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Abstract

This article addresses an analysis of the Load Equivalency Factor (LEF) for off-road trucks. A new LEF curve for single axles with dual wheels covering trucks from 6.0 to 151.42 tons per axle is proposed, converting various magnitudes of damage from wheel loads to damage caused by the standard axle load of 8.2 tons. Then, this damage ratio was raised to the exponent proposed by Pereira (1992), and LEF for the considered loads was obtained. In the determination of LEF from the structural response of the subgrade, it was confirmed that LEF values did not suffer significant variations with the various parameters adopted, encompassing variations in the axle loads between 6 and 151.42 tons, tire pressures of 80.0, 100.0 and 120.0 psi, as well as five different pavement structures. In the study, LEF remained stable even in pavement structures with low and high axle capacities. In order to validate the results, the resulting factors were then compared with those proposed by DNIT (2006), displaying a coefficient of determination of 0.99. The conclusion is that pavements for off-roads trucks can be designed using the procedure recommended by DNIT (2006) for flexible pavement, without extrapolation of the respective LEF curve.

Keywords: load equivalency factor, standard axle load, pavement design, mine roads.

1. Introduction

In iron ore mines that operate on a large-scale, ore transport is usually made by trucks with high axle load capacity. According to Sousa (2011), roads in open pit mines are typically designed by mine planning professionals and executed by operating or infrastructure teams. Unlike the treatment given to highways, Brazilian standards concerning mining activities do not include technical parameters for road design, focusing on regulations directed towards worker safety.

In the design of these roads, the geometric design, the slope of the ramps and the width and curvature radius of the tracks are taken into consideration by mine planning professionals, not contemplating structural projects. This situation leads to a questionable performance of open pit roads, and there is today a certain imbalance when it is compared to the high level achieved in terms of operating technologies, as well as on the evolution of transport vehicles (Sousa, 2011).

The design method of flexible pavements, according to DNIT (2006), takes into account the number of times vehicles pass on these pavements and, for that, it converts the loads of several axles to a standard axle. This is achieved by relating the effects of any axle load to that considered as standard (8.2 tons). Using these relationships, the abacus Axle Load versus Load Equivalency Factor (LEF) was created, which encompasses loads up to 20 tons for single axles and to 30 tons for double and triple tandem axles, being improper for higher loads.

To enable the application of the method DNIT (2006) in the design of open mine roads, i.e., to convert the mining trucks to the standard axle, required is the completion of the said abacus curve for single axles to include axles with much higher loads than those aforementioned.

LEF is used to convert the number of actual traffic requests that request the route in an equivalent number of operations of a standard axle (single axle with dual wheels of 8.2 tons) which, from a theoretical point of view, will result in the same destructive damage to the pavement (Silva, 2009; Silva *et al.* 2011a; Silva *et al.*, 2011b).

According to Pais *et al.* (2013), the calculation of LEF was recently moved from an empirical basis, such as the method proposed in DNIT (2006), to a mechanistic-empirical approach, such as the methods used by Jessup (1996), Hong *et al.* (2006) and Prozzi *et al.* (2007). It should be noted that DNIT is already developing research to elaborate a mechanistic-empirical method that will soon be used for asphalt pavement design.

Zaghloul and White (1994) studied the effect of heavy loads on the Indiana highways and developed the number of equivalent single axle loads (ESALs) based on an analytical approach by considering the permanent deformation of flexible pavements. The approach was developed using a three-dimensional dynamic finite element method for static and dynamic analyses using multi-layer static analysis and actual field measurements. The results showed that the LEF obtained in that analysis agreed with the factors obtained by AASHTO (1993).

More recently, Amorim *et al.* (2015) conducted a study to define the LEFs for flexible pavements by considering the type of axle (single, tandem or tridem), the type of wheels (single and dual) and the constitution of the pavement. The model was developed based on the tensile strain at the bottom of the asphalt layer that is responsible for bottom-up cracking in asphalt pavement. The results of that study allowed the conclusion that the LEFs for single wheels are approximately 10 times greater than those for a dual wheel.

Coffey (2015) has investigated the impact of pavement surface and structural condition on the rolling resistance experienced by large off-road trucks. Terrestrial laser scanning techniques were adapted to provide a quantification of the surface properties of pavements, and also to measure rebound deflection and curvature arising from tire loading. This has revealed that pavement deflection has equal influence to pavement roughness for a loaded truck travelling at operational speeds.

Coffey (2015) has also found that haul road pavement design is best completed via a mechanistic-empirical method. Structural analysis should be completed by a Finite Element Analysis (FEA) with the application of the failure theory presented by Thompson (2011), which includes consideration of the pavement's serviceability and economic importance to a mine owner by considering the daily tonnes hauled along its path. Some indication of the maximum maintenance frequency may be gained by also considering the pavement life predicted by the sub-grade failure theory of Wardle *et al.* (2001). The results of this study suggest that the critical strain should be calculated by nonlinear and three-dimensional FEA.

In this context, the main goal of this study was to investigate LEF for off-road trucks for the application of the design method of flexible pavements according to DNIT (2006). For this purpose, the software Elsym5 was used to simulate loads on different pavement structures, analyzing the deflections found at the top of the subgrade. The exponent used by Silva (2009), Silva *et al.* (2011a) and Silva *et al.* (2011b) to find a relationship between Axle Loads and the correspondent Load Equivalency Factor was applied.

Simulations of different axle loads on some pavement structures with variations of tire inflation pressure were also performed, which compared the deflections at the top of the subgrade in the various types of pavement structures investigated, and assessed their behavior according to the load. Several variations in axle loads were used to relate the deflections at the top of the subgrade, for all the results obtained in the simulations, and for the deflection at the top of the subgrade for the standard axle load, resulting in ratios between them.

By raising these ratios to the exponent used by Silva (2009), Silva *et al.* (2011a) and Silva *et al.* (2011b), LEFs for these loads were determined and the results compared to those found with the abacus Axle Load x LEF presented in DNIT (2006), to validate the values of the axle load previously determined, proposing the curve of the Load Equivalency Factor, thus contemplating loads superior to those of the abacus for single axles presented in DNIT (2006).

2. Methods

In this study, the criterion of maximum deflection or vertical compressive displacement at the top of the subgrade was applied, due to the convenience of developing the research using the software ELSYM 5, which provides horizontal, vertical and maximum shear stresses at any point of the assessed structure. The layers of the pavement structure were considered horizontally infinite, with even and finite thickness, except the last layer, the subgrade, which is considered with semi-infinite thickness. The resilience moduli and the Poisson coefficients were considered constant. The possibilities for the loading settings set up to ten single wheel loads as limit, whose load application is evenly distributed over a circular area on the surface of the system.

Seventeen conventional commercial trucks and off-road types were selected, with different axle loads and tire inflation pressures of 80.0, 100.0 and 120.0 psi, for the assessment of the variation of deflections at the top of the subgrade of five predetermined pavement structures. It should be noted that these structures have different load bearing capacities and were chosen in order to subject them to loading of the axles of trucks with different tire inflation pressures, aiming at the evaluation of the LEF variation. All selected trucks have a simple front single-wheel axle and simple rear twin-wheel axles.

The conventional trucks analyzed were those with axle loads of 6.0, 8.0, 8.2, 10.0, 12.0, 14.0, 16.0, 18.0 and 20.0 tons. The off-road models analyzed were CAT 770, 772, 773G, 775G and 777G, with rear axle load of 24.0, 30.4, 36.4, 42.6 and 60.8 tons, respectively. The mining off-road models analyzed were CAT 785C, 789D and 793F, with rear axle load of 91.1, 121.3 and 151.4 tons, respectively (Table 1).

Pavement structures I, II and III were determined with different numbers and load capacities of layers for consideration of the hypothesis of conversion of LEF results, even with variation in the parameters, as illustrated in Figures 1 (a) to (c). Pavement structures IV and V were selected among several structures proposed by Sousa (2011), as presented in Figures 1 (d) and (e).

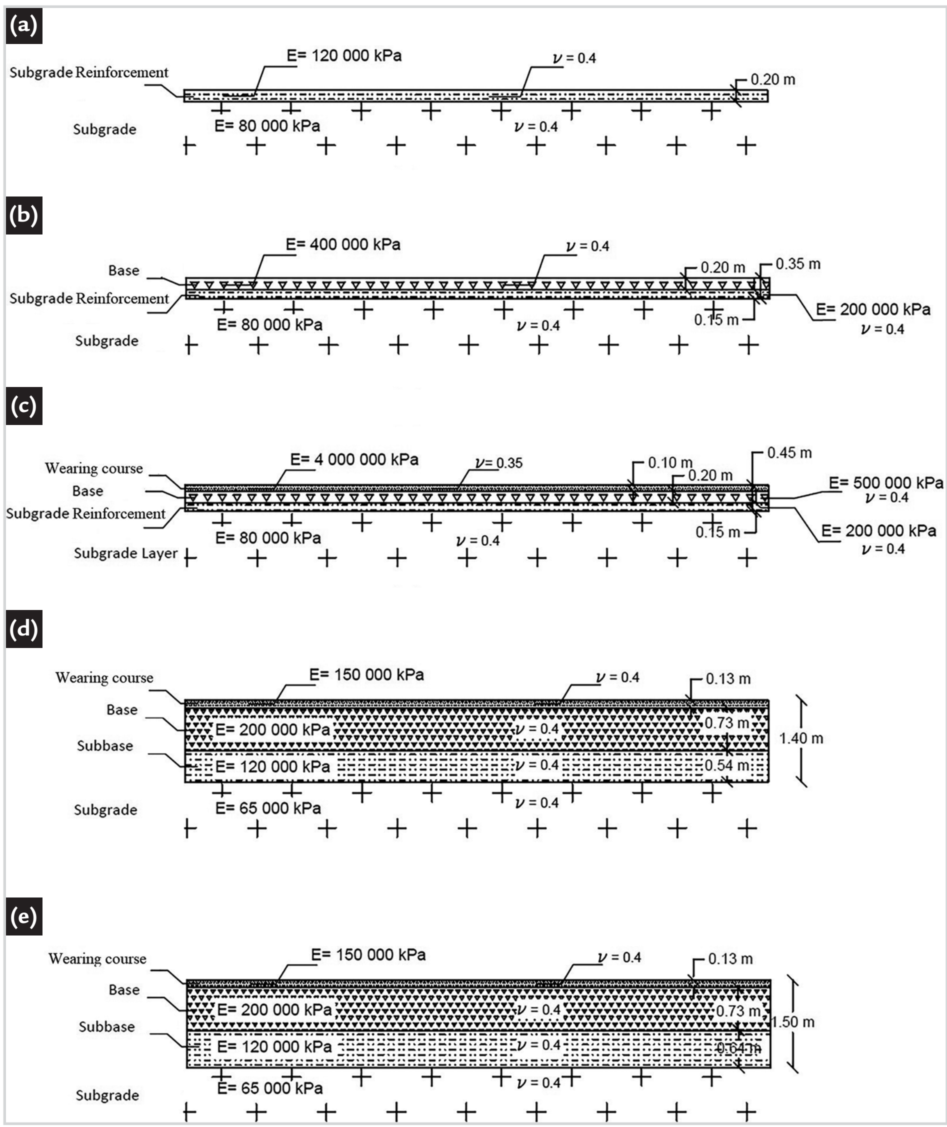

Figure 1
Representation of structures of the analyzed pavements I (a), II (b), III (c), IV (d) and V (e). Layer thickness in meters.

Pavement structures IV and V were adopted by the criterion of lower layer thickness and by the restriction of the deflection limit. The deflection limit adopted by Sousa (2011) was 2000 με. Structures C2 and C6 were selected according to Sousa (2011), as presented in Table 1, which also presents the position of wheels and analysis points on the X-axis for conventional and off-road trucks.

Table 1 - Design of flexible pavements proposed by Souza (2011) and positions of the wheels and of the analysis points on the X-axis for conventional trucks and off-road trucks

Case	Layer Thickness (m)					Optimization requirements		
	Surface asphalt layer	Base layer	Subbase layer	Total	Thickness reduction from the original case	Compliance with strain limit		
C2	1.13	0.73	0.64	1.5	✓	✓		
C6	5.13	0.73	0.54	1.4	✓	✓		
Load on rear axle (ton)	Wheel load (kgf)	Positioning of wheels – X-axis (m)		Positioning of the analyzes in the direction of X-axis (m)				
6	1,500	0	0.33	0	0.08	0.16	0.33	
8	2,000	0	0.33	0	0.08	0.16	0.33	
8.2	2,050	0	0.33	0	0.08	0.16	0.33	
10	2,500	0	0.33	0	0.08	0.16	0.33	
12	3,000	0	0.33	0	0.08	0.16	0.33	
14	3,500	0	0.33	0	0.08	0.16	0.33	
16	4,000	0	0.33	0	0.08	0.16	0.33	
18	4,500	0	0.33	0	0.08	0.16	0.33	
20	5,000	0	0.33	0	0.08	0.16	0.33	
Off-road								
Model	Load on rear axle (ton)	Wheel load (kgf)	Positioning of wheels – X-axis (m)		Positioning of the analyses in the direction of X-axis (m)			
CAT 770	24.0	5,989.5	0	0.58	0	0.14	0.29	0.58
CAT 772	30.4	7,590.0	0	0.64	0	0.16	0.32	0.64
CAT 773G	36.4	9,100.0	0	0.74	0	0.18	0.37	0.74
CAT 775G	42.6	10,659.0	0	0.74	0	0.18	0.37	0.74
CAT 777G	60.8	15,209.0	0	1.15	0	0.29	0.58	1.15
Off-road - Mining								
Model	Load on rear axle (ton)	Wheel load (kgf)	Positioning of wheels – X-axis (m)		Positioning of the analyzes in the direction of X-traffic X (m)			
CAT 785C	91.1	22,780.0	0	1.15	0	0.29	0.58	1.15
CAT 789D	121.3	30,317.5	0	1.15	0	0.29	0.58	1.15
CAT 793F	151.4	37,855.0	0	1.32	0	0.33	0.66	1.32

In determining the LEF for each load, the deflections at the top of the subgrade of each axle load (D_i) were divided by those of the standard axle load (D_s). Then, this damage ratio was raised to the exponent proposed by Pereira (1992) according to Equation 1:

$$LEF = \left(\frac{D_i}{D_S}\right)^{5.959} \qquad (1)$$

The software ELSYM 5 was used to estimate the deflections at the top of the subgrade. The entry data of the program were the number of layers and their respective features [modulus of elasticity E (kPa), Poisson coefficient (ν) and layer thickness (m)], loading features, such as the tire inflation pressure in kPa, the load application radius in meters and the number of load applications and their position in the XY plane, in meters. For the determination of the assessment point, the coordinates were placed on the XY plane and the locations on the Z-axis. The features of each pavement structure analyzed are presented in Table 2.

The deflection at the top of the subgrade was determined by applying any load on a given pavement structure as follows:

1) For structures I, II and III

• The pavement structures were held constant, while varying the tire inflation pressure value;

• The tire inflation pressure was held constant, while varying the pavement structure;

2) For structures IV and V

• Tire inflation pressure was 80 psi, while varying the pavement structure.

Structure I comprised the subgrade improvement layer (0.20 m thick) and the subgrade with moduli of elasticity of 120,000 and 80,000 kPa, respectively; Structure II was composed of the base layer (0.20 m thick), the subgrade improvement layer (0.15 m thick) and the subgrade with moduli of elasticity of 400,000, 200,000 and 80,000 kPa, respectively; Structure III was composed of the surface asphalt layer (0.10 mm thick), the base layer (0.20 m thick), the subgrade improvement layer (0.15 m thick) and the subgrade with moduli of elasticity of 400,0000, 500,000, 200,000 and 80,000 kPa, respectively; Structure IV comprised the surface asphalt layer (0.13 mm thick), the base layer (0.73 m thick), the subbase layer (0.54 m thick) and the subgrade with moduli of elasticity of 150,000, 200,000, 120,000 and 65,000 kPa, respectively; and Structure V was composed by the surface asphalt layer (0.13 mm thick), the base layer (0.73 m thick), the subbase layer (0.64 m thick) and the subgrade with moduli of elasticity of 150,000, 200,000, 120,000 and 65,000 kPa, respectively. All the Poisson coefficients applied were 0.40, except for the asphalt layer of Structure III, which was 0.35. Subgrades were always considered semi-infinite.

Table 2 - Features of pavement structures

Structures	Layers	Layer thickness (m)	Total thickness (m)	Modulus of elasticity (kPa)	Poisson coefficient
I	Subgrade reinforcement	0.20	0.20	120000	0.40
	Subgrade	Infinite		80000	0.40
II	Base	0.20	0.35	400000	0.40
	Subgrade reinforcement	0.15		200000	0.40
	Subgrade	Infinite		80000	0.40
III	Wearing course	0.10	0.45	4000000	0.35
	Base	0.20		500000	0.40
	Subgrade reinforcement	0.15		200000	0.40
	Subgrade	Infinite		80000	0.40
IV	Wearing course	0.13	1.40	150000	0.40
	Base	0.73		200000	0.40
	Subbase	0.54		120000	0.40
	Subgrade	Infinite		65000	0.40
V	Wearing course	0.13	1.50	150000	0.40
	Base	0.73		200000	0.40
	Subbase	0.64		120000	0.40
	Subgrade	Infinite		65000	0.40

3. Results

Figure 2 presents the graphics with the results of tire inflation pressure for Structures I, II and III.

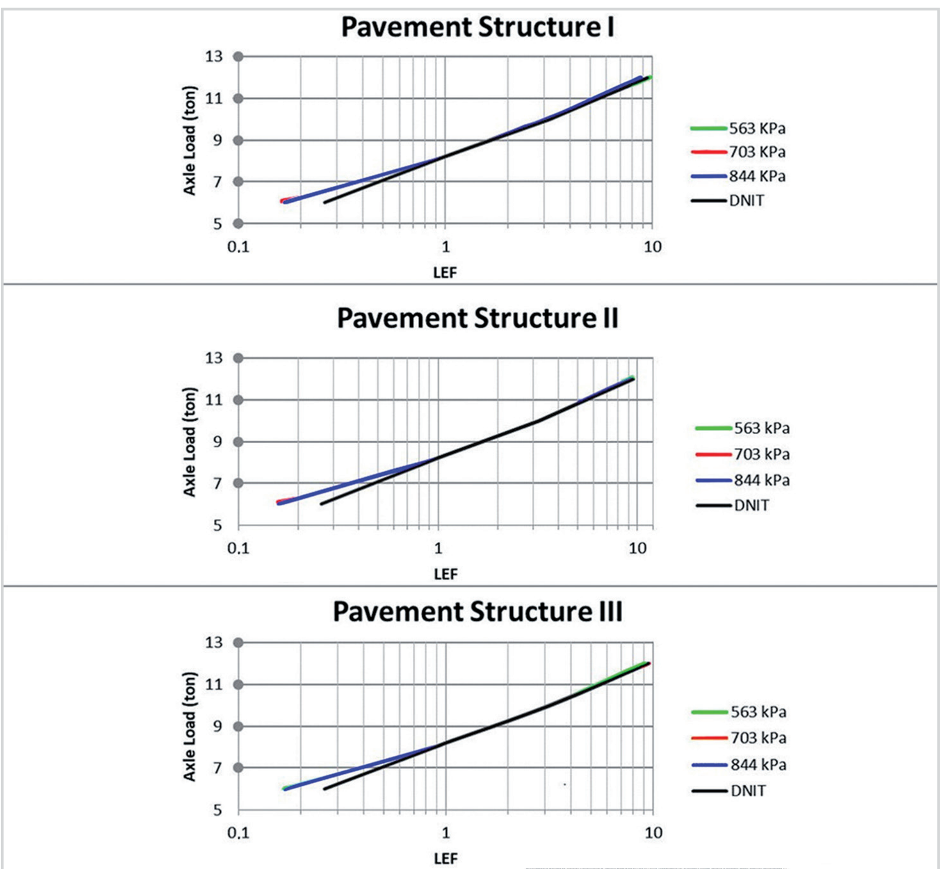

Figure 2
Presents the graphics with the results of tire inflation pressure for Structures I, II and III.

Figure 3 presents the graphics with the results of the variations of Structures I, II and III for the tire inflation pressures applied.

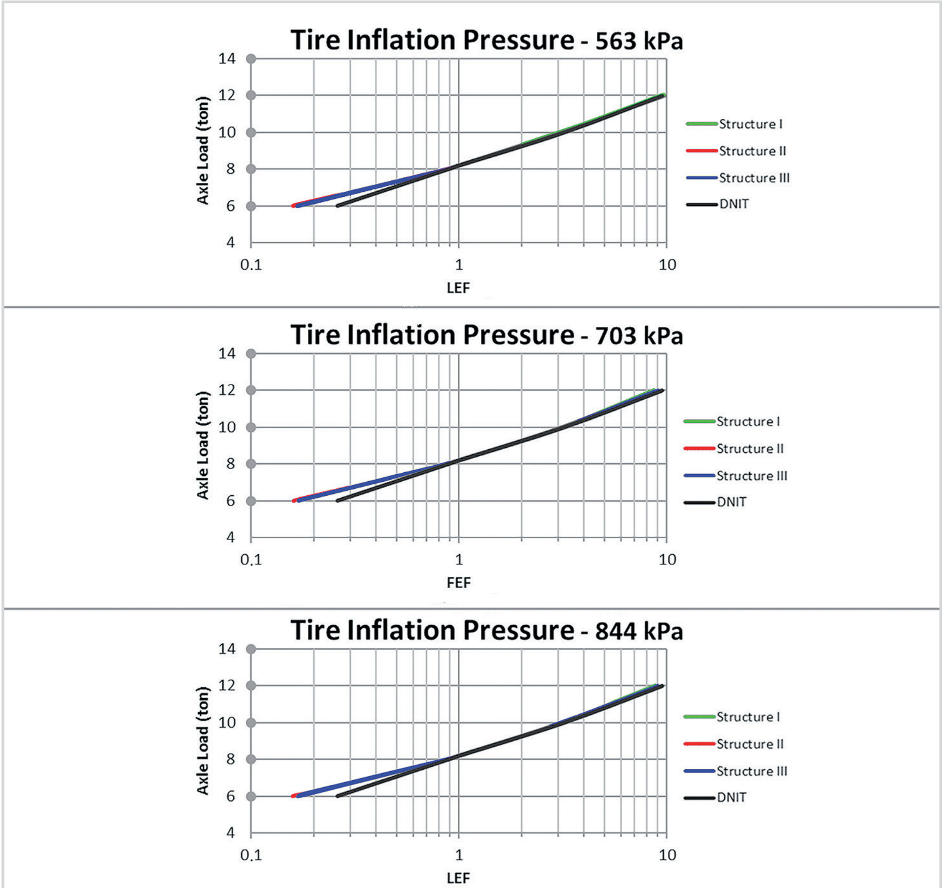

Figure 3
Graphic representation
(Axle Load versus LEF) for tire inflation
pressures of 563, 703 and 844 kPa.

Figure 3 presents the graphics with the results of the variations of Structures I, II and III for the tire inflation pressures applied.

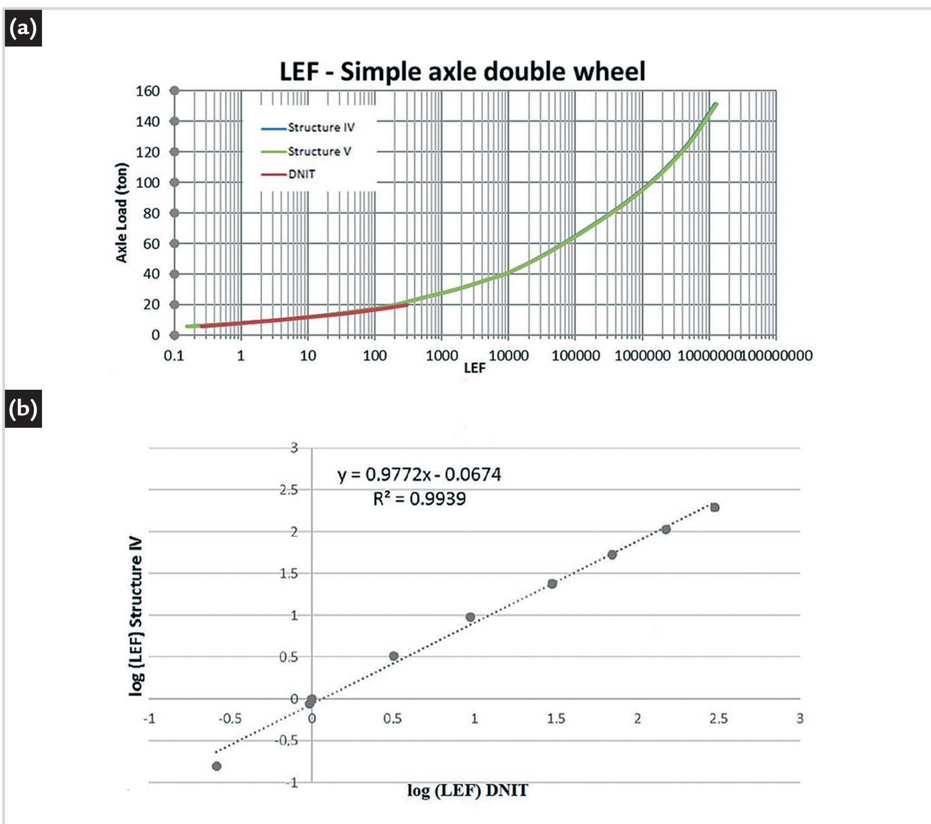

Figure 4
(a) Graphic representation of
LEF results found for off-road trucks
and curve LEF for the single axle with twin
wheels according to DNIT (2006); (b)
Graphic representation of the validation
of results for Structure IV.

4. Discussion

It is noted that there was no significant variation of the values of load equivalency factors for the variation in tire inflation pressure, since the curves are substantially overlapped, as shown in Figures 2 to 4. Data from the abacus Axle Load versus LEF, according to DNIT (2006), were inserted in these charts as comparison criteria, showing that the results obtained in this study are numerically close to those presented by the mentioned source. This confirmation of values credits consistency to the data found here.

It is also seen in Figures 2 to 4 that there was no significant fluctuation of the values of load equivalency factors for the variation of the pavement structure, since the curves are also overlapped. In the figures above, data from the abacus Axle Load versus LEF according to DNIT (2006) were entered as comparison criteria, indicating that the results obtained in this research are also similar to the source material consulted.

With the ratification of the results of this research for conventional trucks, whose hypothesis of convergence of load equivalency factors is sustainable, even with the variation of the parameters of the deflection analysis at the top of the subgrade, it is observed that Sousa (2011) extended the curve of the abacus Axle Load versus LEF presented in DNIT (2006) using mathematical regression, finding the value of 1,640,000 for LEF relative to 167 tons for single axle with twin wheels, through Equation 2, where C is the axle load, in tons.

$$LEF = 0.001 \times C^{4.5951} \quad (2)$$

The result for the LEF obtained using the ratio between deflections at the top of the subgrade of any load and the standard axle load raised to the exponent proposed by Pereira (1992), for a load of 151.42 tons, is equal to 13,000,000.

Comparing the results in this study with the ones found by Sousa (2011), a considerable discrepancy is observed. This finding suggests that the calculation of the load equivalency factors for off-road trucks must be researched more efficiently. This could be achieved by using a mechanistic-empirical method of pavement design. According to Coffey (2015), haul road pavement design is best completed via a Finite Element Analysis (FEA) with the application of the failure theory presented by Thompson (2011).

Based on the results of Figure 4, it is noted that the curves follow the same trend and the results are of the same order of magnitude. Thus, for practical engineering purposes, the differences are negligible for values of axle loads for conventional trucks, that is, with loads up to 20.0 tons.

5. Conclusion

In determining LEF for a single axle with dual wheels in function of the structural response of the subgrade, it was confirmed, through the results on the variation of axle loads between 6.0 and 151.42 tons, tire inflation pressures of 80.0, 100.0 and 120.0 psi and five different pavement structures, that LEF has not suffered relevant variations with the several parameters assumed.

LEF remained stable for the analyzed pavement structures with low carrying capacity, as well as the robust pavement structures with high axle load carrying capacity. This finding validates the flexibility of application of the results.

It is understood, considering this contribution, that the pavements required by off-road trucks can be designed by using the design method of flexible pavements from DNIT (2006), without the need for extrapolation of the LEF curve.

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