EFFECTS OF TRELLEBORG TIRES ON PAVEMENT PERFORMANCE

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This paper presents the results of a study about the effects of tires that have been used in sugar cane plantations, which have very low inflation pressure, on pavement performance. From an agronomic point of view, those tires, which are wider, show a very large bearing capacity, and are known as Trelleborg tires due to the name of the producer, result in economic advantage because the higher absorption of nutrients associated to the lower soil compaction that they cause, i.e., the plants grow taller and there is a reduction in fertilizing costs. Considering that from the farms to the sugar cane industries the trucks travel on paved highways, this study performed a theoretical study about the effects of Trelleborg tires on pavement performance considering their actual footprint, which was obtained in the field and later on transformed into digitalized images. It was verified that Trelleborg tires traveling with tire inflation pressures up to 65 psi (single axles) and 75 psi (tandem axle) are not worse to asphalt pavements than conventional tires carrying the same axle load.

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1. INTRODUCTION

Trelleborg tires are much wider than conventional tires, present high bearing capacity and travel with a very low inflation pressure. The use of Trelleborg tires in collector trucks on sugar cane plantations is interesting because they compact much less the agriculture soil and there is an economic gain due to the improvement of nutrients absorption, growing of the plants and reduction in the number of fertilizing operations.

This paper evaluates the effects of Trelleborg tires on asphalt pavements because part of the way to the sugar industry is on paved roads. Trucks equipped with Trelleborg tires have a Central Tire Inflation (CTI) operated from the truck cabin, which allows the alteration of the tire pressure according to the road surface (lower pressures in the plantation, higher pressures on paved highways).

It presents a comparative analysis between Trelleborg and conventional tires in terms of their effects on pavements, considering the loads effectively applied to pavement-tire contact surface (footprint, Figures 1 and 2).

Figure 1. General view of the area of truck tire footprint determination.
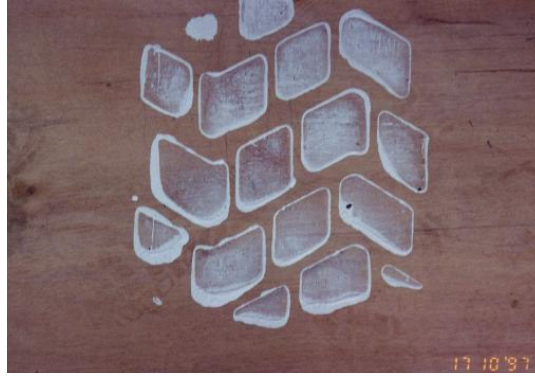
Figure 2. Wooden board showing the truck tire footprint.

Trelleborg tires have been used in compositions formed by a rigid truck with single axle (steering axle) and a tandem axle in the tractor axle, plus a trailer formed by two single axles. Those compositions, very popular in Brazil, are know as "Romeu and Julieta" (Figure 3).
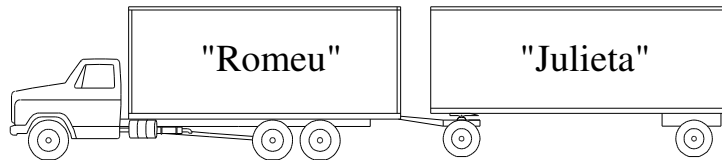

Figure 3. Composition that has used Trelleborg tires the most.

The conventional tires used in the comparative analysis are:
- Goodyear G 186, 22-045 – 10.00 R 20 (radial);
- 900X20 – bias-ply tire (standard axle: single axel, dual wheels, axle load of 80 KN, tire inflation pressure of 563 KPa).

The most used Trelleborg tires are:
- Steering Single Axle (SSA): "steel grip 159", 400/65 – 26.5 12PR (Figure 4);
- Tandem Axle (TD): "twin 423", 600/50B – 22.5 160D (Figure 5);
- Rear Single Axle (RSA): "twin 404", 700/40B – 22.5 162D (Figure 6).

Figure 4. Trelleborg tire in a steering single (40 cm wide).

Figure 5. Trelleborg tire in a tandem axle (60 cm wide).

Figure 6. Trelleborg tire in a rear single axle (70 cm wide).

2. ANALYSIS OF TRELLEBORG TIRES LOAD DISTRIBUTION ON PAVEMENTS

2.1 Load Equivalent Factors Concept

The repeated loads applied by highway traffic are the main cause of pavement deterioration. The load equivalency concept has been widely used for the quantification of the cumulative effect of traffic loads.

Due to the great variability of traffic loading factors (axle loads, tire pressures, suspension systems, axle types, wheel types, vehicle speed, pavement condition etc.), their effects must be expressed by a common denominator, the Load Equivalent Factor (LEF), which allows the conversion of different load applications in an equivalent number of applications of the standard axle. The LEF is very important for pavement design and for pavement performance under actual traffic prediction. It is also important for cost allocation, since it allows the comparison between damages caused by different loading applications.

This work considers empirical-mechanistic LEF that result from structural analysis of two pavements. It is based on performance prediction models, which quantifies the relative effects of Trelleborg and conventional tires as a function of their main structural responses.

A loading application to a pavement structure changes the structural responses (stresses, strains and displacements). Some structural responses are associated to particular forms of pavement deterioration and consequently, they can be used for pavement performance prediction. According to Miner (1945), the unitary damage caused by a single load application corresponds to the inverse of the necessary number of applications to completely deteriorate the pavement. Thus, LEF can be defined by the ratio between the damage caused by the loading condition under analysis and the damage caused by a standard axle:

$$LEF_i = [1/N_i /1/N_0] = N_0 /N_i \tag{1}$$

where:

- LEF_i: Load Equivalent Factor for loading condition i;
- N_o: admissible number of loading applications of the standard axle;
- N_i: service life for the loading condition i.

Empirical-mechanistic models are used for the prediction of pavement service life as a function of structural responses:

$$N = a \times (1/\rho)^b \tag{2}$$

where:

- a and b are associated to the structural response considered, the test performed and the pavement type;
- ρ is a generic structural response.

Thus, it is possible to express the LEF as a function of the ratio between structural responses associated to the loading condition under analysis (ρ_i) and the standard axle (ρ_0):

$$LEF_i = \left(\rho_i \middle/ \rho_0 \right)^b \tag{3}$$

Mechanistic-empirical LEF depends on computer programs that calculate pavement structural responses and performance prediction models that relate the pavement service life to the magnitude of the structural response.

2.2 Pavement Deterioration Mechanisms

A pavement can deteriorate according to different mechanisms. In this work only deterioration mechanisms associated to the structural damage caused by traffic loading repetitions are considered: fatigue cracking and permanent deformation (rutting). Deterioration mechanisms such as raveling are not considered, since they are caused mainly by non-traffic related problems (i.e., construction problems, and environmental factors).

2.2.1 Fatigue Cracking of the Asphalt Layer
The repetitions of elastic (resilient) deformation provoqued by traffic loadings cause the iniciation and propagation of crackings in the surface layer. Fatigue cracking (from the bottom to the top of the surface layer) is the main pavement deterioration process in Brazilian highways (Queiroz, 1981). It is also considered by all pavement design methods as a major problem, the one associated to the biggest share of pavement maintenance and rehabilitation costs.

Fatigue cracking is influence by the loading magnitude, including the effects of factors such as axle load, tire pressure, axle type, wheel type, tire type and suspension system. It is also dependent of asphalt layer properties (asphalt cement type, aggregate type, compaction etc.). It is a complex process that becomes more critical with the pavement aging.

Deacon (1965) was the first to propose that the rupture of asphalt mixtures by fatigue is a function of the horizontal tensile strain at the bottom of the surface layer. Finn et al. (1977) presented two of the most utilized equations that relate the horizontal tensile strain ($\varepsilon_{ht,1}$) to the number of admissible applications of the 80 kN standard axle:

$$\log(N)_{(\leq 10\%)} = 15.947 - 3.291 \times \log(\varepsilon_{ht,1}) - 0.854 \times \log(E_1) \tag{4}$$

$$\log(N)_{(\geq 45\%)} = 16.086 - 3.291 \times \log(\varepsilon_{ht,1}) - 0.854 \times \log(E_1) \tag{5}$$

where E_1 is in ksi (1,000 psi = 7,032 kPa) and $\varepsilon_{ht,1}$ is times 10^6.

2.2.2 Rutting

The accumulation of permanent deformation in the wheel tracks is a structural damage that affects safety and can cause acquaplanning. Rutting develops gradually with loading applications, which densify pavement layers or cause plastic deformation by shearing stresses.

Although rutting is the most important pavement deterioration in many countries, it does not have the same relative importance for Brazilian highways (Queiroz, 1981). More than 95% of Brazilian paved highways present rutting less than 5 mm, which is much lower than the maximum limits normally presented in the literature (20 to 25 mm).

The general structure of rutting prediction models as a function of traffic loadings is similar to the fatigue cracking models. Several equations relate the rutting limit (20 mm, for instance) achieved after N applications of the standard axle to the structural response vertical compressive strain at the top of subgrade (ε**Error!Error!Error!**$_{vc,m}$):

$$N = a \times \left(\frac{1}{\varepsilon_{vc,m}} \right)^b \tag{6}$$

The basic difference among those equations is in the values of parameters a and b, that are obtained from correlations between mechanistic analysis and surveys of in-service pavements. Claessen et al. (1977), based on AASHO Road Test data, obtained $a = 6.15 \times 10^{17}$ and $b = 4.00$.

2.2.3 Mechanistic-Empirical Equations for LEF Calculation

Considering the structural distresses fatigue cracking and permanent deformation, in this work two mechanistic-empirical equations are used for LEF determination:

$$LEF(\varepsilon_{ht,1}) = \left[(\varepsilon_{ht,1})_i / (\varepsilon_{ht,1})_0 \right]^{3.291} \tag{7}$$

$$LEF(\varepsilon_{vc,m}) = \left[(\varepsilon_{vc,m})_i / (\varepsilon_{vc,m})_0 \right]^4 \tag{8}$$

2.3 Computer Program ELSYM5

The computer programa ELSYM5 (Elastic Layered System), used for calculation of stress, strains, and displacements in a linear-elastic layered system, was developed at the University of California, Berkeley. The loading condition is described by two out of three itens: load, contact pressure, and radius of the surface loading. The input data are: layer properties (thickness, elasticity modulus, and Poisson ratio), position and magnitude of the surface loads (uniformly distributed on identical circular surfaces, perpendicular to the pavement layers), and coordinates for the determination of structural responses.

The sequence followed in this work for the evaluation of the relative effects of Trelleborg and conventional tires is: the input data (axle load, number of tires, and tire-pavement contact area) is used by ELSYM5 to calculate structural responses, which are used for the determination of LEF corresponding to each loading condition. Since the LEF depends on the pavement structure, two different pavements, representatives of the most used in the State of Sao Paulo, Brazil, and already used by Fernandes Jr. (1995) in a study about supersingle tires: Structure A (Figure 7), associated to a light to medium traffic, and Structure B (Figure 8), associated to a medium to heavy traffic. From a statistic point of view, different structures represent replicates, reinforcing the conclusions about the effects of traffic loading factores.
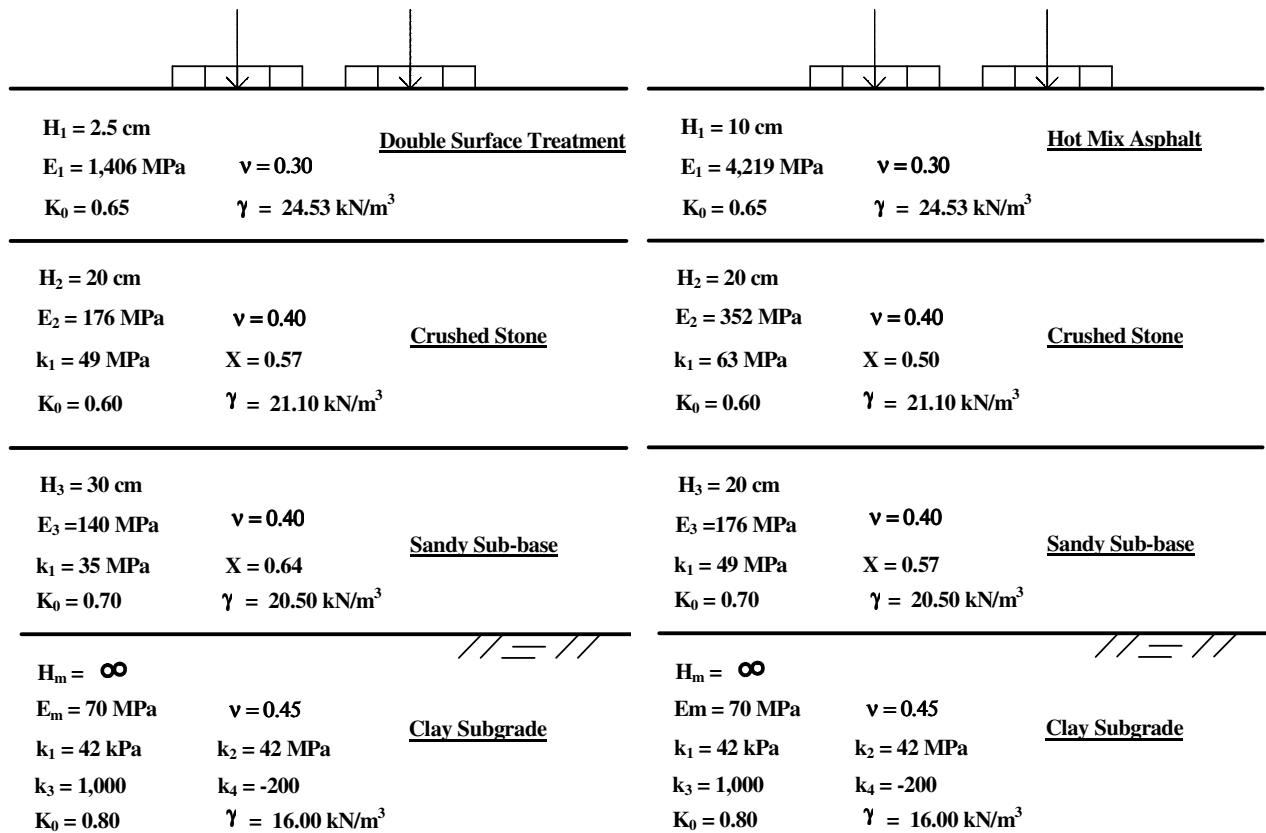
Structure A	Structure B
$H_1 = 2.5$ cm **Double Surface Treatment** $E_1 = 1,406$ MPa $\nu = 0.30$ $K_0 = 0.65$ $\gamma = 24.53$ kN/m^3	$H_1 = 10$ cm **Hot Mix Asphalt** $E_1 = 4,219$ MPa $\nu = 0.30$ $K_0 = 0.65$ $\gamma = 24.53$ kN/m^3
$H_2 = 20$ cm **Crushed Stone** $E_2 = 176$ MPa $\nu = 0.40$ $k_1 = 49$ MPa $X = 0.57$ $K_0 = 0.60$ $\gamma = 21.10$ kN/m^3	$H_2 = 20$ cm **Crushed Stone** $E_2 = 352$ MPa $\nu = 0.40$ $k_1 = 63$ MPa $X = 0.50$ $K_0 = 0.60$ $\gamma = 21.10$ kN/m^3
$H_3 = 30$ cm **Sandy Sub-base** $E_3 = 140$ MPa $\nu = 0.40$ $k_1 = 35$ MPa $X = 0.64$ $K_0 = 0.70$ $\gamma = 20.50$ kN/m^3	$H_3 = 20$ cm **Sandy Sub-base** $E_3 = 176$ MPa $\nu = 0.40$ $k_1 = 49$ MPa $X = 0.57$ $K_0 = 0.70$ $\gamma = 20.50$ kN/m^3
$H_m = \infty$ **Clay Subgrade** $E_m = 70$ MPa $\nu = 0.45$ $k_1 = 42$ kPa $k_2 = 42$ MPa $k_3 = 1,000$ $k_4 = -200$ $K_0 = 0.80$ $\gamma = 16.00$ kN/m^3	$H_m = \infty$ **Clay Subgrade** $E_m = 70$ MPa $\nu = 0.45$ $k_1 = 42$ kPa $k_2 = 42$ MPa $k_3 = 1,000$ $k_4 = -200$ $K_0 = 0.80$ $\gamma = 16.00$ kN/m^3

Figure 7. Pavement Structure A: double surface treatment.

Figure 8. Pavement Structure B: hot mix asphalt.

3. RESULTS

3.1 Contact Area

It was necessary the determination of the effective contact areas, since the Trelleborg tires present footprint with many void spaces, what invalidate the hypothesis that the contact pressure is equal to the tire inflation pressure. The followed procedure was: a hydraulic jack raised the semi-axle (Figure 9), the tires were painted (Figure 10), a wooden board was placed below the tires and, finally, the hydraulic jack was downloaded (Figure 11).

In the office, the tire-pavement contact surfaces were digitalized (Figure 2). With the computer programa AutoCAD there was the determination of contact areas and gravity centers. Tables 1, 2, and 3 present the effective contact areas and Tables 4, 5, and 6 present the contact pressures, for different Trelleborg tires and different tire inflation pressures. There was also the determination of the effective tire-pavement contact area for conventional tires in a standard axle (single axle, dual wheels, axle load of 80 kN and tire inflation pressure of 563 kPa):

- Tire-pavement effective contact area: 780.28 cm^2 (the tire load divided by the tire inflation pressure is the theoretical area = 729.90 cm^2);
- Average tire-pavement contact pressure: 73 psi (tire inflation pressure = 80 psi).
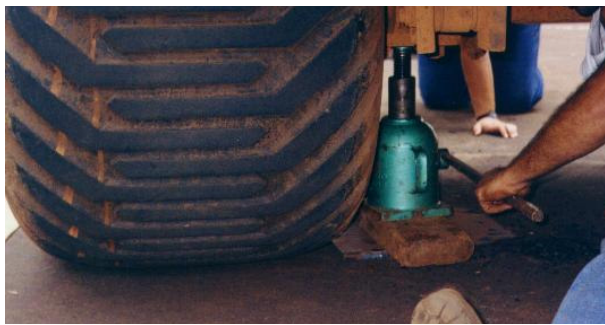

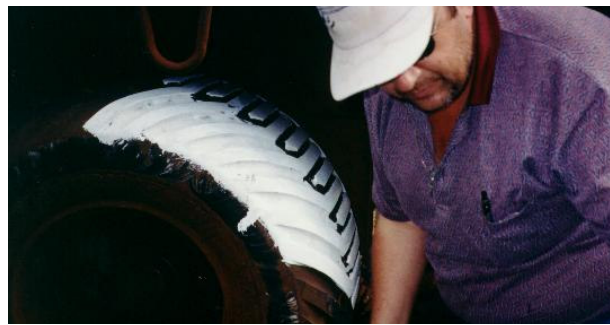**Figure 9. Lifting the semi-axle for tire painting.**

Figure 10. Detail of tire painting.

Figure 11. General view after downloading the tire on the wooden board.

Table 1. Effective tire-pavemen contact area (cm²): Steering Single Axle (SSA).

LOADING CONDITION	TRELLEBORG TIRE (40 cm)			CONVENTIONAL TIRE	
	p = 176 KPa	p = 317 Kpa	p = 458 KPa	p = 563 KPa	p = 704 KPa
Unloaded	503.15	417.58	327.40	272.88	325.99
(Theoretical)	*(996.94)*	*(553.85)*	*(383.44)*	*(329.34)*	*(263.48)*
Loaded	685.14	497.36	423.98	334.56	323.52
(Theoretical)	*(1367.23)*	*(680.45)*	*(525.86)*	*(391.65)*	*(313.32)*

Table 2. Effective tire-pavemen contact area (cm²): Tractor Tandem Axle (TTA).

LOADING CONDITION	TRELLEBORG TIRE (60 cm)			CONVENTIONAL TIRE	
	p = 197 KPa	p = 366 Kpa	p = 528 KPa	p = 563 KPa	p = 704 KPa
Unloaded	433.08	340.19	306.18	404.19	342.05
(Theoretical)	*(1142.13)*	*(616.24)*	*(427.26)*	*(391.65)*	*(313.32)*
Loaded	973.80	679.75	610.68	654.08	718.56
(Theoretical)	*(2314.32)*	*(1280.41)*	*(864.01)*	*(827.81)*	*(665.81)*

Table 3. Effective tire-pavemen contact area (cm²): Rear Single Axle (RSA).

LOADING CONDITION	TRELLEBORG TIRE (70 cm)			CONVENTIONAL TIRE	
	p = 176 KPa	p = 317 Kpa	p = 458 KPa	p = 563 KPa	p = 704 KPa
Unloaded	449.39	369.91	365.72	-	-
(Theoretical)	*(1082.39)*	*(601.33)*	*(416.30)*	-	-
Loaded	1493.86	780.75	756.18	-	-
(Theoretical)	*(2848.39)*	*(1582.44)*	*(1095.53)*	-	-

Table 4. Average tire-pavement contact pressure (psi): SSA.

LOADING CONDITION	TRELLEBORG TIRE (40 cm)			CONVENTIONAL TIRE	
	p = 25 psi	p = 45 psi	p = 65 psi	p = 80 psi	p = 100 psi
Unloaded	50	60	76	97	81
Loaded	50	62	81	94	97

Table 5. Average tire-pavement contact pressure (psi): TTA.

LOADING CONDITION	TRELLEBORG TIRE (60 cm)			CONVENTIONAL TIRE	
	p = 28 psi	p = 52 psi	p = 75 psi	p = 80 psi	p = 100 psi
Unloaded	74	94	105	78	92
Loaded	67	98	106	101	93

Table 6. Average tire-pavement contact pressure (psi): RSA.

| LOADING CONDITION	TRELLEBORG TIRE (70 cm)			CONVENTIONAL TIRE	
	p = 25 psi	p = 45 psi	p = 65 psi	p = 80 psi	p = 100 psi
Unloaded	60	73	74	-	-
Loaded	48	91	94	-	-

3.2 Load Equivalent Factors

The strucutural analysis of pavements presented in Figures 7 and 8 determined the horizontal tensile strain at the bottom of the surface layer and the vertical compressive strain at the top of the subgrade, for all axles of two truck compositions, one with Trelleborg tires and another with conventional tires. It was also considered two loading conditions (loaded and unloaded).

To the use of ELSYM5 for strucutural responses calculation, every tire-pavement contact surface of the footprints (Figures 12, 13, and 14) was represented by a circular surface with equivalent area and same location of the gravity center. The results are presented in Table 7.
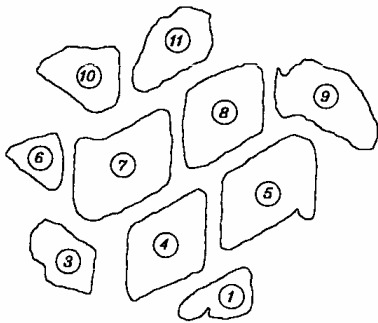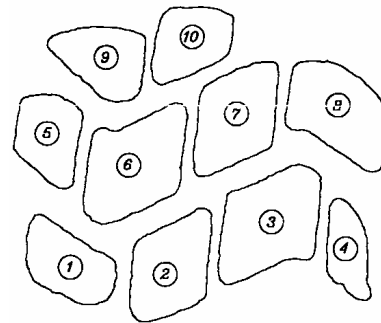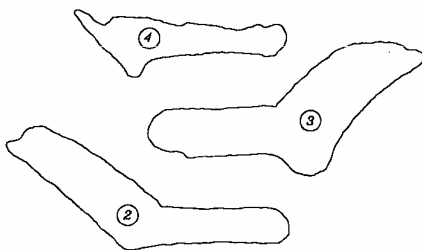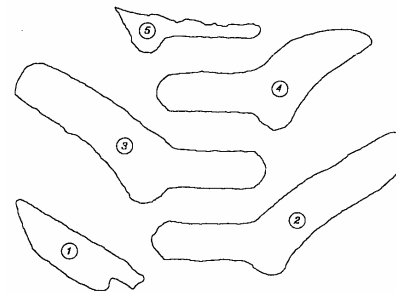

a) Unloaded   b) Loaded

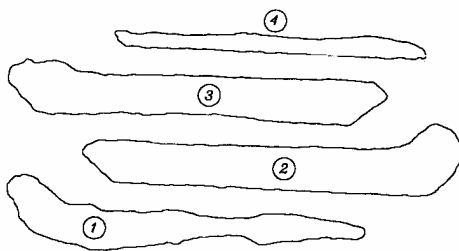**Figure 12. Trelleborg tire footprint, steering single axle (40 cm), tire pressure = 65 psi.**

a) Unloaded   b) Loaded
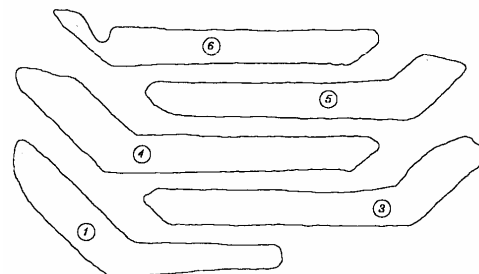
Figure 13. Trelleborg tire footprint, tandem axle (60 cm), tire pressure = 75 psi.

a) Unloaded   b) Loaded

Figure 14. Trelleborg tire footprint, rear single axle (70 cm), tire pressure = 65 psi.

Table 7. Load Equivalent Factors: average values from the analysis of Pavement Structures A and B.

Loading Condition		TRELLEBORG TIRES				CONVENTIONAL TIRES			
		SSA	TA	RSA	Σ	SSA	TA	RSA	Σ
Unloaded	$\varepsilon_{ht,1}$	0.23	1.25	0.38	1.86	0.50	0.73	0.29	1.52
	$\varepsilon_{vc,m}$	0.09	0.37	0.11	0.57	0.06	0.21	0.06	0.32
Loaded	$\varepsilon_{ht,1}$	0.66	1,64	1,14	3,39	5,86	3.30	2.08	11,24
	$\varepsilon_{vc,m}$	0.20	6,19	4,03	10,41	0.14	3.66	2.44	6.23

4. CONCLUSIONS

A truck composition equipped with Trelleborg tires presents lower LEF (i.e., less pavement deterioration) than a truck composition equipped with conventional tires, when considered the effects on the asphalt layer, associated to fatigue cracking damage, mainly at the critical condition (loaded). Otherwise, when considering the effects on the subgrade, associated to rutting damage, a truck composition with Trelleborg tires presents higher LEF.

For Brazilian highways, fatigue cracking is much more important than rutting, which could suggest that Trelleborg tires cause less damage to pavements than conventional tires, particularly for light to medium traffic roads, such as the highways used for the sugar cane transportation from the plantations to the industry. In any case, however, it can be concluded that Trelleborg tires traveling with tire inflation pressures up to 65 psi (single axles) and 75 psi (tandem axle) are no worse for asphalt pavements than conventional tires carrying the same axle load.

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