EFFECTS OF TRAFFIC LOADING ON PORTUGUESE AND BRAZILIAN PAVEMENTS PERFORMANCE

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ABSTRACT

This work investigated the effects of traffic loading on the performance of Portuguese and Brazilian pavements, aiming to contribute to a better technical regulation of heavy vehicles and cost allocation related to the pavement deterioration. Among the traffic loading factors, this work considered axle load, axle type, tire inflation pressure, and wheel type. Six pavement structures were analyzed where three of them are representative of Portuguese pavements, and three are representative of Brazilian pavements. It was performed a linear-elastic mechanistic analysis to determine two structural responses: horizontal tensile strain at the bottom of the asphalt layer and vertical compressive strain at the top of subgrade, associated to the most important pavement distresses in Portugal and Brazil, respectively fatigue cracking and rutting. With the structural responses it was calculated load equivalence factors, which represent the relative effect of each loading condition and allow the analysis of Portuguese and Brazilian pavement design methods and regulations.

Keywords: axle load, axle type, tire pressure, wheel type, load equivalence factors.
INTRODUCTION

The repeated loads applied by heavy vehicles are the main cause of pavement deterioration. The analysis of the interaction between pavement and vehicle is not easy because trucks do not damage the pavement in the same way in each pass, due to vehicle heterogeneity, axle load, frequency and number of load applications, axle type, suspension type, wheel type, tire type, tire inflation pressure, speed (loading time) and traffic loading path. There are also the influence of the properties of pavement materials, operational condition of traffic and environmental factors.

This work analyzed the vehicle-pavement interaction, which is fundamental to pavement design and pavement management. It aims to contribute to the improvement of technical regulations of heavy vehicles and to a better cost allocation, based on the distresses caused in the pavements. Thus, this work analyzed the effects of axle load, axle type (steering axle, single axle, tandem and tridem), wheel type, and tire inflation pressure on the pavements performance.

The deterioration of a pavement is due to, mainly, the axle load. There is no straight relationship between the total weight of a truck and the pavement performance, although the toll plazas in Portugal and Brazil charge the vehicles based on the number of axles, what can be unfair, since for two trucks with the same load, the higher the number of axles the lower is the damage caused in the pavement.

The axle load is the main traffic loading factor, although it is not the only one. There is an exponential relationship between axle load and pavement deterioration. The AASHO Road Test results indicated a power of 4 and since that it has been used the term “fourth power law” to express the relative effects of different axle loads. However, more important that the power, which can vary from 3 to 6, for flexible pavements, is that there is a huge increase in pavement deterioration when the axle load increases.

The quantification of the relative damage caused by axle loads can be done under static condition, since the dynamic effects on the pavement performance are a function of the speed, pavement roughness and vehicle suspension system (1). The legal limits of axle loads in Portugal and in Brazil are presented in Table 1.

The most common wheel types are single wheel in the steering axle, dual wheel in the other axles, and supersingle tires in steering axles or substituting the dual wheel. The supersingle tires represent an advantage in terms of net weight increasing and operational costs reduction. However, many studies, for instance the Special Report 227 of the Transportation Research Board (2), show many evidences that the supersingle tires can cause more pavement deterioration than the conventional dual wheel.

During the AASHO Road Test (3) the tire inflation pressure varied from 528 to 563 kPa (75 e 80 psi). With the born of radial tires in early 1970’s, there was a huge increase in tire pressures, with average values ranging between 703 and 738 kPa (100 and 105 psi) in the USA. In Europe, supersingle tires run with tire inflation pressure around 985 kPa (140 psi). In Brazil, the average tire pressure is 844 kPa or 120 psi (4).

A higher tire pressures has caused concerns about their effects on the pavement performance, mainly to the surface layer. There is also a secondary effect associated to higher tire inflation pressure, since it increases the stiffness of the suspension system and the dynamic loads.

The alternatives to control the effects of high tire pressures can be through legal enforcement (i.e., limitation of tire pressure) or engineering (better asphalt mixture design
methods, better quality control and quality assurance of paving works, better strategies for pavement maintenance and rehabilitation).

LOAD EQUIVALENCE FACTORS

The knowledge of the cumulative effect of traffic loading is fundamental for pavement design and management. Due to the great variability of traffic loading factors, their cumulative effect has to be expressed by a Load Equivalence Factor (LEF).

The LEF is the most used concept in pavement design (5). It allows the conversion of different load applications in an equivalent number of applications of a standard-axle, allowing the pavement design for a given number of years, the prediction of pavement performance under the actual traffic, and the allocation of responsibilities over the maintenance and rehabilitation costs, because the LEF permits the comparisons between different traffic loadings. The LEF can be presented as following (6):

- Suppose two loading conditions (L_X and L_Y) applied to pavements with the same structure and in the same environment;
- Suppose that if a given deterioration (D) reaches a previously defined value (D*) some maintenance or rehabilitation is required;
- Suppose, finally, that D* occurs after N_X applications of L_X and N_Y applications of L_Y. By definition, N_X and N_Y are equivalent and the ratio between N_Y and N_X is equal to the LEF of L_Y related to L_X.

If L_Y is a standard loading condition (for instance, axle load of 80 kN, single axle, dual wheel, tire pressure equal to 563 kPa or 80 psi, at a speed of 55 km/h), so the ratio between N_Y e N_X is a factor able to convert N_X in an equivalent number of applications of the standard-axle. In a more generic way, the Load Equivalence Factors can be expressed as following:

\[
LEF_i = \frac{N_o}{N_i}
\]  

(1)

where N_o is the number of applications of the standard-axle to the deterioration level D* and N_i is the number of applications of the loading condition i to the same deterioration level D*.

The LEF concept depends on the deterioration (fatigue cracking, rutting, serviceability index), the specified level of deterioration (PSI equal to 2,0, rutting equal to 20,0 mm), the bearing capacity of the pavement layers, and, obviously, the traffic loading factors. In Brazil, there are two most used LEF (7, 8) and in Portugal it is used the LEF of AASHTO (7).

MECHANISTIC ANALYSIS

The traffic loading changes the structural responses of the pavement and some responses can be used for pavement deterioration prediction. The damage caused by one load application corresponds to the inverse of the number of applications (N) necessary to reach the end of the service-life (9). Thus, the Load Equivalence Factors can be defined by the following:

\[
LEF_i = \left[ \frac{1}{N_i} \right] \cdot \left[ \frac{1}{N_o} \right] = \frac{N_o}{N_i}
\]  

(2)

where:
- LEF_i: Load Equivalence Factor for loading condition i;
- $N_0$: service-life (number of loading applications) for the standard-axle;
- $N_i$: service-life for loading condition $i$.

For the development of empirical-mechanistic LEF it is necessary a performance model that relates a given level of pavement deterioration (normally the end of the service-life) to the number of repetitions of a structural response.

In this work it was considered structural responses associated to fatigue cracking and rutting, the most important structural distresses in Portugal and in Brazil:

- **Horizontal tensile strain at the bottom of the asphalt layer** ($\varepsilon_{ht,1}$);
- **Vertical compressive strain at the top of the subgrade** ($\varepsilon_{vc,m}$).

In general, the empirical-mechanistic models consider just one structural response:

$$N = a \times \left( \frac{1}{\rho} \right)^b$$  \hspace{1cm} (3)

where:

- $N$: number of load applications;
- $a$ and $b$: constants;
- $\rho$: structural response.

It is possible to express the LEF as a power of the ratio of two structural responses, one to the loading condition under analysis ($\rho_1$) and other to the standard-axle ($\rho_0$):

$$N = \left( \frac{\rho_1}{\rho_0} \right)^b$$  \hspace{1cm} (4)

The empirical-mechanistic LEF depends on software for structural responses calculation and performance models. It is important to mention that they are particularly important for studies about new loading configurations.

**Fatigue Cracking of Asphalt Layer**

Fatigue cracking is the main distress observed in Portuguese and Brazilian highways, the one responsible for most of the expenditures in pavement maintenance and rehabilitation. The pavement service-life ($N$, number of load applications of the standard-axle) related to fatigue cracking is a function of the horizontal tensile strain at the bottom of the asphalt layer (10):

$$N = a \left( \frac{1}{\varepsilon_{ht,1}} \right)^b$$  \hspace{1cm} (5)

One available equation was developed based on the AASHO Road Test results and a laboratory investigation of structural properties of 27 field sections (11), and its power is 5.16. Another very used one includes the Modulus of the asphalt layer (12), and its power is 3.291. In this work, it was used the power 4 for the determination of LEF.

**Rutting**

Another very important distress for Portuguese and Brazilian pavements is rutting. The framework of the models for rutting prediction is similar to the one used for fatigue cracking prediction. Normally it is considered 20 mm as the rutting limit.

$$N = a \left( \frac{1}{\varepsilon_{vc,m}} \right)^b$$  \hspace{1cm} (6)
A version of the Shell Method of Pavement Design \((13, 14)\) presents different values for the constant \(a\), depending on the confidence level. However, the power is always the same, 4, which is the value adopted in this work for LEF calculation.

**Calculus of the Structural Responses**

Although linear-elastic analysis presents limitations because just a few pavement materials have a constant modulus of elasticity, some researches \((15)\) validate their use for estimation of the structural behavior of pavements under traffic loading. Besides that, the linear-elastic analysis allows a fast determination of structural responses and need just a few parameters. This work used the software ELSYM5 and BISAR.

The input data is: layer properties (thickness, Modulus of Elasticity, Poisson ratio), position and magnitude of the circular loads, and the coordinates of the evaluation points. In this work, the distance between the centers of the loads in the case of dual wheel was 33 cm, and the distance between axles in a tandem or tridem was 120 cm. The structural responses were determined under the center of the loads and at points in intermediate positions, at the bottom of the asphalt layer \((e_{hl,1})\) and at the top of the subgrade \((e_{vc,m})\).

The axle loads considered for the analysis performed in this work were:

- Single Axles: 40, 60, 80, 100, 120 e 140 kN;
- Tandem: 160, 180 e 200 kN;
- Tridem: 220, 240 e 260 kN.

**Material Properties**

Six pavement structures, typical of Portuguese and Brazilian highways, were considered (Tables 2 and 3): heavy traffic (PT 01, BR 01), medium traffic (PT 02, BR 02) and light traffic (PT 03, BR 03).

**RESULTS AND ANALYSIS OF THE RESULTS**

Figures 1 and 2 are example of the Load Equivalence Factors obtained with the analysis of single axles, for different levels of tire inflation pressure and different pavement structures, considering the vertical compressive strain at the top of the subgrade. The results show the effects of wheel type on the LEF and also the reference values (AASHTO and DNER, Brazilian Highway Agency). Similarly, Figures 3 and 4 show the results for tridem axles.

Figures 5 and 6 are example of the Load Equivalence Factors obtained with the analysis of steering axles and tandem axles, respectively, for different pavement structures and considering the horizontal tensile strain at the bottom of the asphalt layer. The results show the effects of wheel type and tire inflation pressure on the LEF and also the reference values (AASHTO and DNER).

In 2004 there was a weighing campaign in several points of the Portuguese highway network. The results show that there is no considerable axle overload, as exemplified by Figure 7, which presents a summary of the results obtained with tridem axles.

For all of the loading conditions analyzed, steering axle and supersingle tires result in higher LEF, i.e., they are three to five times worse to the pavements than the dual wheel. Although the difference is higher for structural responses at the surface layer, even for
structural responses at the subgrade, steering axles and supersingle tires result in LEF at least 50% higher than the ones of the dual wheel.

The effects of tire inflation pressure are significant for structural responses at the asphalt layer. An increase from 563 kPa (80 psi), which was the tire pressure during the AASHO Road Test, to 844 kPa (120 psi), which is the average among the heavy vehicles circulating in Portuguese and Brazilian highways, can increase up to 50% the LEF.

The effects of traffic loading factors are not the same for different structural response. The horizontal tensile strain at the surface layer is very sensitive to axle load, wheel type and tire inflation pressure. The vertical compressive strain at the subgrade is more influenced by axle load followed by the wheel type, with almost no effect of tire inflation pressure, which can explain the use of just one chart for LEF determination for steering axles (single wheel) and for single axles with dual wheel, and the absence of concerns about tire pressure regulations in the past.

CONCLUSIONS

The results of this work can be useful for the improvement of pavement design methods, asphalt mixture design procedures and also for technical regulations of heavy vehicles. But it is necessary broad economic studies, with the participation of legislators, universities, research centers, transport operators, constructors, transportation industries and users, aiming at establishing legal limits for dimensions and weights that do not affect the performance of the transportation infrastructure and, at the same time, improve the transportation efficiency.

The AASHTO Guide (7) combined steering axles (single wheels) to single axles with dual wheel for the determination of LEF, and this became the general rule for other pavement design methods. However, this work shows clearly that single wheels (steering axles or supersingle tires) present LEF three to five times higher than conventional dual-wheel, carrying the same load. Particularly in Brazil, based on data collected in urban areas (4), the steering axles are responsible for a great share of the pavement deterioration. Even so, the legal limits for steering axles increased, in 1993, form 50 kN to 60 kN. Thus, it is recommended to return to the previous legal limit, allowing axle loads between 50 kN and 70 kN just for steering axles equipped with supersingle tires.

Portuguese and Brazilian pavement design methods should consider a specific LEF for single axle with single wheel instead of using the same LEF developed for single axle with dual wheel. This action has been postponed for many years and the effects of steering axles and supersingle tires have been hugely underestimated. The tire inflation pressure is also an important issue and should be considered for pavement design, asphalt mixture design, technical regulation and also a cost allocation criterion.

Finally, it is important to emphasize that empirical-mechanistic LEF, like the ones used in this work, are very useful tools for studies about the relative effects of traffic loading factors.

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REFERENCES


LIST OF TABLES

TABLE 1  Legal limits of axle load in Portugal and Brasil
TABLE 2  Mechanical properties of representative structures of Portuguese pavements
TABLE 3  Mechanical properties of representative structures of Brazilian pavements
LIST OF FIGURES

FIGURE 1 LEF for single axles, obtained with Structures PT 01 and BR 03, considering the structural response $\varepsilon_{vc,m}$ and tire pressure of 80 psi
FIGURE 2 LEF for single axles, obtained with Structures PT 01 and BR 03, considering the structural response $\varepsilon_{vc,m}$ and tire pressure of 120 psi
FIGURE 3 LEF for tridem axles, obtained with Structures PT 01 and BR 03, considering the structural response $\varepsilon_{vc,m}$ and tire pressure of 80 psi
FIGURE 4 LEF for tridem axles, obtained with Structures PT 01 and BR 03, considering the structural response $\varepsilon_{vc,m}$ and tire pressure of 120 psi
FIGURE 5 LEF for steering axles, obtained with Structures PT 03 and BR 02, considering the structural response $\varepsilon_{ht,1}$
FIGURE 6 LEF for tandem axles, obtained with Structures PT 03 and BR 02, considering the structural response $\varepsilon_{ht,1}$
FIGURE 7 Summary of data from weighing stations in Portugal – Tridem Axles
<table>
<thead>
<tr>
<th>COUNTRY</th>
<th>Steering Axle (kN)</th>
<th>Single Axle (kN)</th>
<th>Tandem (kN)</th>
<th>Tridem (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portugal</td>
<td>75</td>
<td>100 a 120(^1)</td>
<td>120 a 200(^2)</td>
<td>210 a 240(^2)</td>
</tr>
<tr>
<td>Brazil</td>
<td>60</td>
<td>100</td>
<td>170</td>
<td>255</td>
</tr>
</tbody>
</table>

\(^1\) as a function of being a non-power axle or a power axle;  \(^2\) as a function of distance between axles.
<table>
<thead>
<tr>
<th>STRUCTURE</th>
<th>PT 01</th>
<th>PT 02</th>
<th>PT 03</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer</td>
<td>H (cm)</td>
<td>E (MPa)</td>
<td>v</td>
</tr>
<tr>
<td>1</td>
<td>5,0</td>
<td>4500</td>
<td>0,35</td>
</tr>
<tr>
<td>2</td>
<td>7,0</td>
<td>5500</td>
<td>0,35</td>
</tr>
<tr>
<td>3</td>
<td>18,0</td>
<td>6500</td>
<td>0,35</td>
</tr>
<tr>
<td>4</td>
<td>20,0</td>
<td>200</td>
<td>0,35</td>
</tr>
<tr>
<td>m (subgrade)</td>
<td>-</td>
<td>70</td>
<td>0,35</td>
</tr>
<tr>
<td>STRUCTURE</td>
<td>H (cm)</td>
<td>E (MPa)</td>
<td>v</td>
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<td>-</td>
<td>-</td>
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<tr>
<td>m (subgrade)</td>
<td>-</td>
<td>70</td>
<td>0,45</td>
</tr>
</tbody>
</table>
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FIGURE 2 LEF for single axles, obtained with Structures PT 01 and BR 03, considering the structural response $\varepsilon_{vc,m}$ and tire pressure of 120 psi.
FIGURE 3 LEF for tridem axles, obtained with Structures PT 01 and BR 03, considering the structural response $\varepsilon_{vc,m}$ and tire pressure of 80 psi
FIGURE 4 LEF for tridem axles, obtained with Structures PT 01 and BR 03, considering the structural response $\varepsilon_{vc,m}$ and tire pressure of 120 psi
FIGURE 5 LEF for steering axles, obtained with Structures PT 03 and BR 02, considering the structural response $\varepsilon_{ht,1}$
FIGURE 6 LEF for tandem axles, obtained with Structures PT 03 and BR 02, considering the structural response $\varepsilon_{ht,1}$
FIGURE 7 Summary of data from weighing stations in Portugal – Tridem Axles