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EQUIVALENT AXLE LOAD FACTORS FOR DESIGN OF RIGID PAVEMENTS DERIVED FROM FATIGUE CRITERIA

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Abstract. This paper presents determination of equivalent axle load factors for rigid pavements on the basis of fatigue criteria used in mechanistic-empirical methods of pavement design. Fatigue criteria for selected methods of rigid pavement design and analysis are presented. These criteria were used to derive the formulas to calculate equivalent axle load factors. It was found that formulas derived for rigid pavements are much more complex than the well known "fourth power equation". The equivalency factors depend on the slab thickness and bending strength of cement concrete and other pavement parameters. There are considerable differences between the equivalent axle load factors derived from different fatigue criteria used in various design methods. The presented analysis indicates that traffic analysis and fatigue criteria should be interrelated.

Keywords: equivalent axle load factor, fatigue criteria, rigid pavements, pavement analysis.

1. Introduction

The equivalent axle load factors are the basis for determining the design traffic and, as a consequence, for designing of road pavements. The most frequently used formula to calculate equivalent axle load factor has the following exponential form:

$$F_j = \left(\frac{Q_j}{Q_s}\right)^n, \tag{1}$$

where F_j – equivalent axle load factor; Q_s – standard axle load, kN; Q_j – actual axle load, kN. In most cases the exponent $n = 4$ is used in practical design, and therefore the Eq (1) is called "fourth power equation". For rigid pavements the exponent n varies from 4 to 12 in different design methods. The German catalogue of typical pavement structures *(RStO 01 – Richtlinien für die Standardisierung des Oberbaues von Verkehrsflächen* [Guidelines for the Standardization of the Pavement Structures of Trafficked Areas]) uses the standard axle load of 100 kN and the same uniform exponent $n = 4$ for all types of pavement structures (flexible, semi-rigid and rigid). *French Design Manual for Pavement Structures* (Corté, Goux 1996*)* uses standard axle load of 130 kN and the formula for traffic aggressiveness in form similar to Eq (1) with exponent $n = 12$ for rigid and semi-rigid pavements, and $n = 5$ for flexible pavements. The Polish catalogues of flexible, semi-rigid and rigid pavements issued in 1997 and 2001 use standard axle load of 100 kN or 115 kN and exponent $n = 8$ for rigid and $n = 4$ for flexible and semi-rigid pavements. The *AASHTO Guide for Design of Pavement Structures* (1993) uses standard axle load of 80.1 kN (18-kip) and presents a set of tables which define the equivalent axle load factors for rigid pavements in relation to actual axle load, axle configuration, concrete slab thickness and terminal value of p_t – Present Serviceability Index. It can be derived from the AASHTO Guide 1993 for rigid pavements that exponent n is in a range of 4. For example, for a concrete slab $h = 280$ mm and terminal value of $p_t = 2.5$ the exponent n varies from 4.13 to 4.36. In Lithuania, according to Sivilevičius and Šukevičius (2007), the impact of traffic load on pavement structures is expressed by the formula same as Eq (1) presented above with exponent $n = 4$, and with standard axle load either 80 kN or 100 kN.

Load axle equivalency for rigid pavements was a subject of several studies. Hajek and Agarwal (1990) analyzed main factors affecting load equivalency in relation to spacing of dual and triple axles. Gillespie *et al.* (1993) analyzed effects of heavy vehicles in relation to axle load, axle suspension, axle spacing, tire inflation pressure, tire configuration, type of pavement (rigid and flexible) and environmental factors. Hajek (1995) proposed simplified approach for load equivalency in form independent of pavement related variables. Lin *et al.* (1996) performed full-scale test on a section of rigid pavement in Taiwan and found that the AASHTO 1993 method yields reliable prediction of

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the equivalency factors. Kuo and Lin (2001) used finite element model and developed regression formulas for equivalent axle load factors for rigid pavements. These factors differed significantly from the AASHTO 1993 method and were strongly related to concrete slab thickness, slab support and material strength. Chatti *et al*. (2004) used the laboratory determined fatigue equations to develop load equivalency factors for multiple axle loading. Lukanen (2005) described field tests on instrumented flexible and rigid pavement sections in Minnesota and mechanistic analysis which was used to determine axle load factors. In case of flexible pavements they were able to predict axle load factors on the basis of measured strains but in case of rigid pavements the analysis was more problematic and obtained results were not clear due to erratic strain behaviour in concrete slabs. Smith and Diefenderfer (2009) developed trucks equivalent standard axle factors for flexible and rigid pavements on the basis of weigh-in-motion data. Modern analysis used in regulation policy of permitting super heavy vehicles with multiple axles is based on fatigue cracking life of pavement structures (Chen *et al*. 2005; Salama *et al.* 2006). Wardęga (2010) used weighing in motion data on roads in Poland and determined truck equivalency factors for flexible and rigid pavements.

This paper presents analytical determination of axle load equivalency factors for rigid pavements based on fatigue criteria applied in modern mechanistic-empirical methods of pavement design. It was proven in this paper that the equivalency between actual and standard axle load is not constant but is strongly dependent on the fatigue law which is applied in pavement design. For rigid pavements axle load equivalency is much more complex than exponential Eq (1) and depends on several variables, including material properties and pavement structure characterization. The similar approach was used by the author earlier for flexible and semi-rigid pavements (Judycki 2010).

2. Concept for calculation of equivalent axle load factors based on the fatigue criteria

The following formula is used to convert the actual, varying axle loads to equivalent standard axles:

$$N_s = F_j N_j, \tag{2}$$

where N_s – number of equivalent standard axles corresponding to the N_j number of actual axles; N_j – number of actual axles; F_j – equivalent axle load factor. Axle equivalency means that N_s number of standard axles Q_s has the same damaging effect to a specific pavement structure as N_j number of actual axles of Q_j load.

The equivalent axle load factor F_j defines the damage to a pavement by pass of the actual axle in question relative to the damage by pass of a standard axle load (Huang 2003). In this paper the following practical definition of equivalent axle load factor F_j will be used: "The equivalent axle load factor F_j is the ratio between the total number of passes to failure N_{fs} of a standard axles of defined load Q_s to the total number of passes to failure N_{fj} of the actual axles of Q_j load, for the same pavement structure":

$$F_j = \frac{N_{fs}}{N_{fj}}. \tag{3}$$

In the mechanistic-empirical methods of design for rigid pavements the fatigue cracking of cement concrete slab caused by repeated axle loading is taken into account. The fatigue laws, which determine the number of axle load applications which can be carried out by the pavement until the failure occurs, are described by the following general function:

$$N_f = f(\sigma, K), \tag{4}$$

where σ – bending stresses generated in a concrete slab under a specific axle load; K – group of parameters characterizing a pavement layer, accounted for by the fatigue law, which are not related to the axle load. When combined, the formulas (3) and (4) yield the following formula for calculating the equivalent axle load factor:

$$F_j = \frac{N_{fs}}{N_{fj}} = \frac{f(\sigma_s, K)}{f(\sigma_j, K)}, \tag{5}$$

where the stresses σ depend on the axle load and pavement design parameters. Subscripts j and s denote the values for the actual and standard axles respectively. From the form of fatigue laws it can be seen that functions $f(\sigma, K)$ may be expressed as a product of two independent functions:

$$f(\sigma, K) = f_1(\sigma) f_2(K). \tag{6}$$

For this reason the parameters K in Eq (5) will be reduced and the formula for equivalent axle load factor will take a simpler form:

$$F_j = \frac{N_{fs}}{N_{fj}} = \frac{f_1(\sigma_s)}{f_1(\sigma_j)}. \tag{7}$$

The further analysis in this paper is based on the assumption that the traffic induced stresses σ in cement concrete slabs are linearly proportional to the axle load value Q:

$$\sigma = \beta Q, \tag{8}$$

where β – proportionality coefficient, depending on the characteristics of a pavement structure and the loading parameters. This assumption is justified by the Westergaard formula for stresses in concrete slabs (Eq (24)).

3. Derivation of equivalent axle load factors for rigid pavements

Fatigue criteria for rigid pavements were selected from different design guides. These are: Portland Cement Association (PCA), Zero-Maintenance Fatigue Model (USA), AASHTO 2004 and French design method. For the sake of simplicity the same symbols will be used across different criteria in further analyses. However, sometimes the symbols used here differ from those used in the original formulas of the respective design methods. The symbols used below are: Q – axle load; Q_s – standard axle load; Q_j – actual axle load in question; N – number of load applications; N_f – fatigue life, number of load applications to fatigue cracking of concrete slab; $SR = \frac{\sigma}{R_b}$ – stress ratio; σ – tensile stress in bending, induced in concrete slab by wheel load; R_b – bending strength of cement concrete slab, named also as modulus of rupture; β – proportionality factor between traffic induced stress σ in concrete slab and axle load Q, as in Eq (8).

Portland Cement Association (PCA) fatigue criteria. The PCA design method uses the following fatigue criteria for cement concrete slabs (Huang 2003):

$$\log N_f = 11.737 - 12.077SR \;\; for \;\; SR \ge 0.55, \tag{9}$$

$$N_f = \left(\frac{4.2577}{SR - 0.4325}\right)^{3.268} \;\; \text{for} \;\; 0.45 < SR < 0.55, \tag{10}$$

$$N_f \text{ unlimited for } SR \le 0.45. \tag{11}$$

The first of the above formulas, for $SR \ge 0.55$, is held in most practical cases and will be considered further. It can be rearranged to obtain the following formula for calculating the equivalent axle load factor:

$$\log F_j = \log\frac{N_{fs}}{N_{fj}} = \log N_{fs} - \log N_{fj} = 12.077\left(\frac{\sigma_j - \sigma_s}{R_b}\right), \tag{12}$$

Assuming linear relation between stress and axle load in form $\sigma = \beta Q$ it was obtained that:

$$\log F_j = 12.077\frac{\beta(Q_j - Q_s)}{R_b} \;\; \text{for} \;\; SR \ge 0.55. \tag{13}$$

Zero-Maintenance Design Fatigue Model (USA). It is expressed by the following formula, developed by Darter and Barenberg (1977), with assumption of failure probability equal to 24%:

$$\log N_f = 16.61 - 17.61SR, \tag{14}$$

In a similar way as before it was obtained that:

$$\log F_j = 17.61\frac{\beta(Q_j - Q_s)}{R_b}. \tag{15}$$

New AASHTO 2004 Mechanistic-Empirical Method. The new *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures (Final Report NCHRP Project 1-37A, TRB, NRC, 2004)* sponsored by AASHTO and FHA uses the following fatigue equation which is similar to the earlier model developed in USA by ERES/COE (Darter 1988):

$$\log N_f = C_1\left(\frac{R_b}{\sigma}\right)^{C_2} + 0.4371, \tag{16}$$

where $C_1 = 2.0$ and $C_2 = 1.22$ – calibration constants. Therefore:

$$\log F_j = \log N_{fs} - \log N_{fj} = C_1\left[\left(\frac{R_b}{\sigma_s}\right)^{C_2} - \left(\frac{R_b}{\sigma_j}\right)^{C_2}\right]. \tag{17}$$

After substituting $\sigma = \beta Q$ and transforming:

$$\log F_j = C_1\left[\left(\frac{R_b}{\beta Q_s}\right)^{C_2} - \left(\frac{R_b}{\beta Q_j}\right)^{C_2}\right]. \tag{18}$$

Ker *et al*. (2008) found that the AASHTO 2004 mechanistic-empirical model was not adequate and proposed a new model on the bases of Long-Term Pavement Performance data-base.

French Design Manual (1996). The French criterion in design of rigid pavements is tensile stress induced in cement concrete slab. The value of admissible tensile stress is given by the relation (Corté, Goux 1996):

$$\sigma_{t,ad} = \sigma_t(N)k_r k_d k_c k_s, \tag{19}$$

where $\sigma_{t,ad}$ – admissible tensile strength at bending at N load applications; $\sigma_t(N)$ – stress for which failure on a 360-day concrete sample is obtained for N load applications; k_c – factor to account for the observed behaviour of the same type of pavement; k_d – factor to account for discontinuities in the base layer; k_r – factor to account for variability of test results and calculation risk; k_s – factor to account for errors in preparation of base underneath concrete slab.

The fatigue law for the cement treated materials is represented by the following expression:

$$\sigma(N) = (1 + 6\gamma)\left(\frac{N}{10^6}\right)^b \sigma_0, \tag{20}$$

where N – number of load applications inducing stress σ(N); γ, β – empirical coefficients; σ_0 – initial strength. If actual axle Q_j induces in concrete slab stress σj and standard axle load Q_s induces stress σ_s, than:

$$\sigma_j = (1 + 6\gamma)\left(\frac{N_{fj}}{10^6}\right)^b \sigma_0 \text{ and } \sigma_s = (1 + 6\gamma)\left(\frac{N_{fs}}{10^6}\right)^b \sigma_0. \tag{21}$$

After rearrangement the following formula for equivalency load factor is obtained:

$$F_j = \frac{N_{fs}}{N_{fj}} = \left(\frac{\sigma_s}{\sigma_j}\right)^{\frac{1}{b}} = \left(\frac{\beta Q_s}{\beta Q_j}\right)^{\frac{1}{b}} = \left(\frac{Q_s}{Q_j}\right)^{\frac{1}{b}}. \tag{22}$$

Table 1. Derived formulas for equivalent axle load factors F_j

No.	Fatigue criterion	Equation for equivalent axle load factors F_j
1.	Portland Cement Association Method (PCA)	$\log F_j = 12.077\dfrac{\beta(Q_j - Q_s)}{R_b}$ for $R \geq 0.55$
2.	Zero-Maintenance Design Fatigue Model (USA)	$\log F_j = 17.61\dfrac{\beta(Q_j - Q_s)}{R_b}$
3.	New AASHTO 2004 Mechanistic-Empirical Method	$\log F_j = C_1\left[\left(\dfrac{R_b}{\beta Q_s}\right)^{C_2} - \left(\dfrac{R_b}{\beta Q_j}\right)^{C_2}\right]$
4.	French Design Method	$F_j = \left(\dfrac{Q_j}{Q_s}\right)^{16}$

For cement concrete slab in the French method $\dfrac{1}{b} = -16$, thus:

$$F_j = \left(\frac{Q_j}{Q_s}\right)^{16}. \tag{23}$$

Table 1 presents the derived formulas for equivalency factors for cement concrete pavements.

4. Relation between stresses induced in concrete slab and axle load

The single axle load with single wheels is considered further. For rigid pavements stresses induced by a single wheel load are calculated from the Westergaard equations at 3 points of the slab: centre, edge and corner. The most appropriate point for designing the jointed concrete pavement is the transverse slab edge, which is most frequently loaded by each passing wheel. The following formula is applied for the slab edge:

$$\sigma = \frac{0.529P}{h^2}(1+0.54\nu)\left(\log\frac{Eh^3}{kb^4} - 0.71\right), \tag{24}$$

where σ – tensile stresses in bending, kN/m^2; $P = \dfrac{Q}{2}$ – wheel load (half of a single axle load Q, kN); E – modulus of elasticity of cement concrete slab, kN/m^2; ν – Poisson's ratio of cement concrete slab; h – thickness of concrete slab, m; k – modulus of subgrade reaction, kN/m^3; $b = \sqrt{1.6a^2 + h^2} - 0.675h$, m, for $a < 1.724h$, $b = a$, for $a > 1.724h$, a – radius of contact area between tire and pavement, m. Tensile stresses in bending of concrete slabs are linearly proportional to the wheel load P, and consequently to the axle load Q. The proportionality coefficient in relation $\sigma = \beta Q$ is equal to:

$$\beta = \frac{0.2645}{h^2}(1+0.54\nu)\left(\log\frac{Eh^3}{kb^4} - 0.71\right). \tag{25}$$

Units are important in this relation. Axle load Q is always expressed in kN, thus σ should be expressed in kN/m^2 and β in 1/m^2, other values are in units given above as explanation to Eq (24).

Table 2 presents calculated values of the proportionality coefficient β for the following input data: diameter of tire contact area a = 0.15 m, modulus of elasticity of cement concrete $E = 35 \times 10^6$ kN/m^2, Poisson's ratio of cement concrete ν = 0.15, modulus of subgrade reaction $k = 100 \times 10^3$ kN/m^3 and $k = 200 \times 10^3$ kN/m^3, thickness of concrete slab h = from 0.16 to 0.30 m. It can be seen that the β coefficient is strongly related to thickness of the slab h and less to modulus of subgrade reaction k.

Table 2. Proportionality coefficient β in 1/m^2 between stresses σ in kN/m^2 induced in concrete slab and axle load Q in kN for selected concrete slab and load parameters

Slab thickness h, m	β, 1/m^2, for $k = 100 \times 10^3$ kN/m^3	β, 1/m^2, for $k = 200 \times 10^3$ kN/m^3
0.16	31.938	28.576
0.18	26.606	23.950
0.20	22.475	20.323
0.22	19.211	17.433
0.24	16.589	15.095
0.26	14.454	13.180
0.28	12.692	11.594
0.30	11.223	10.267

5. Calculated values of equivalent axle load factors F_j

Calculated values of factors F_j depend on the fatigue law and are related to actual and standard axle load, bending strength of concrete and coefficient β, which in turn depends on thickness of a concrete slab h, modulus of subgrade reaction k and other pavement parameters. The formulas presented in Table 1 were used and calculations were performed for the following data: thickness of concrete slab h from 0.16 m to 0.30 m, modulus of subgrade reaction $k = 100 \times 10^3$ kN/m^3 and $k = 200 \times 10^3$ kN/m^3, bending strength $R_b = 5.5 \times 10^3$ kN/m^2, standard axle load Q_s = 100 kN, actual axle load Q_j varied from 20 to 160 kN.

Results of calculations are presented in Figs 1–3. The AASHTO 2004 formula was omitted in data presented in Figs 1–3, because it gave results evidently different from all others. Figs 1 and 2 present calculated values of equivalent axle load factors F_j and exponents n in relation $F_j = \left(\frac{Q_j}{Q_s}\right)^n$. It is clearly seen from Fig. 1 that the form of fatigue criteria have significant effect on equivalent axle load factor. The exponent n is constant in the French method ($n = 16$) and nearly constant in the AASHTO 1993 method ($n \approx 4$). In other methods n increases with the increase of the actual axle load Q_j. The exponent n derived from the Zero Maintenance and PCA models increases from 4 and 6 at $Q_j = 20$ kN to 10 and 14 at $Q_j = 160$ kN, respectively. The n value from the new AASHTO 2004 method, not shown in Fig. 1, is exceptionally high ($n > 20$). Fig. 2 indicates that the effect of slab thickness on F_j and on the exponent n is very significant. Axle load aggressiveness, indicated by exponent n, is greater for thinner slabs. The effect of slab thickness should be considered in practical analysis. Fig. 3 shows that the effect of subgrade reaction k on equivalency factor is much less significant than the effect of slab thickness h and this effect can be omitted in practical analysis.

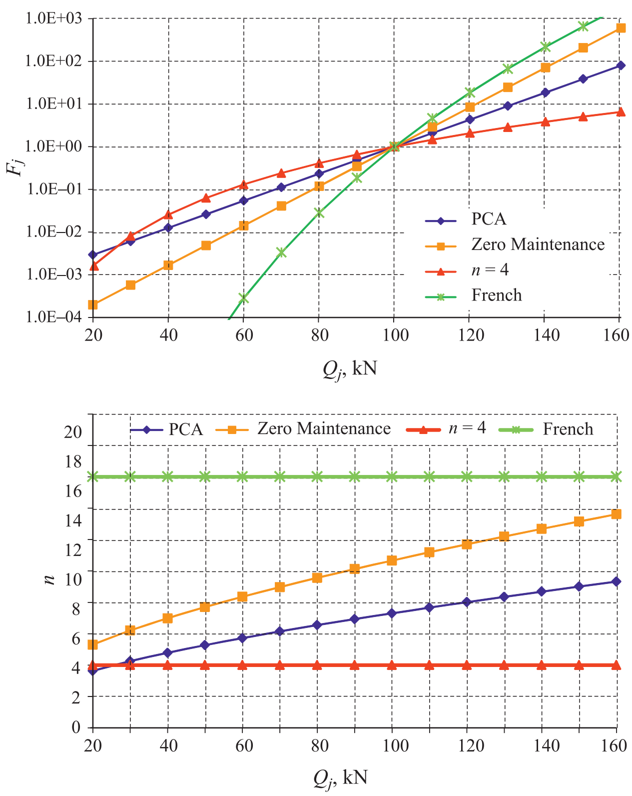

Fig. 1. Equivalent axle load factors F_j and exponents n in relation $F_j = \left(\frac{Q_j}{Q_s}\right)^n$ obtained from various fatigue criteria as a function of actual axle load Q_j (for $h = 0.26$ m, $R_b = 5.5 \times 10^3$ kN/m^2, $E = 35 \times 10^6$ kN/m^2; $k = 100 \times 10^3$ kN/m^3, $Q_s = 100$ kN)

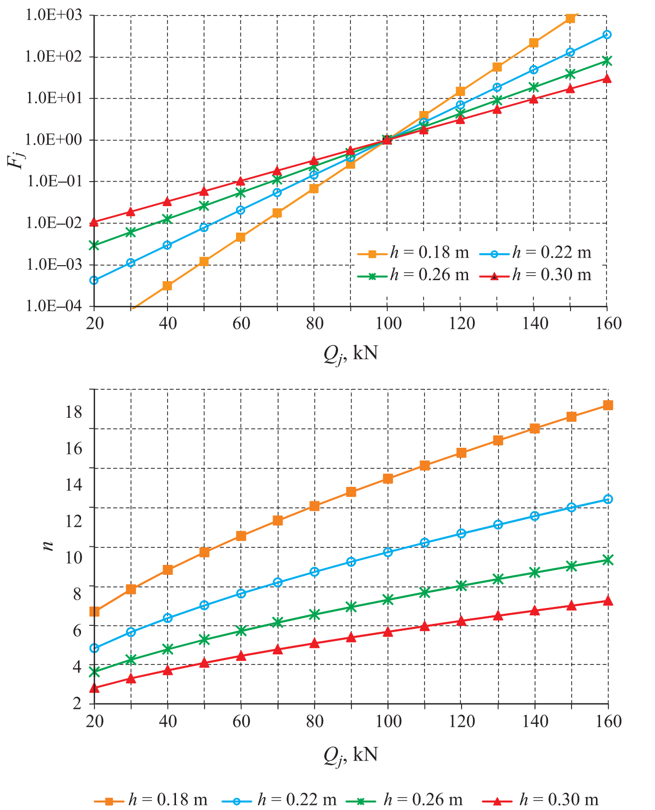

Fig. 2. Equivalent axle load factors F_j and exponent n in relation $F_j = \left(\frac{Q_j}{Q_s}\right)^n$ obtained from Portland Cement Association criterion as a function of actual axle load Q_j and thickness of concrete slab h (for $R_b = 5.5 \times 10^3$ kN/m^2, $E = 35 \times 10^6$ kN/m^2; $k = 100 \times 10^3$ kN/m^3, $Q_s = 100$ kN)

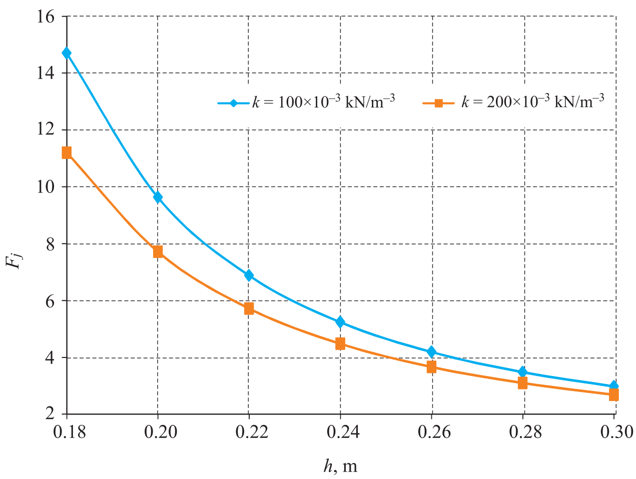

Fig. 3. Equivalent axle load factors F_j obtained from Portland Cement Association criterion in relation to thickness of concrete slab h and modulus of subgrade reaction k (for standard axle load $Q_s = 100$ kN and actual axle load $Q_j = 120$ kN)

6. Conclusions

The equations for calculating the equivalent axle load factors F_j for rigid pavements derived from the analysed fatigue criteria are much more complex than "fourth power equation" which is often used in practice. Equivalency factors F_j obtained for rigid pavements deviate strongly from the "fourth power equation". The value of exponent n determined from some fatigue criteria depends on several factors, such as the form of applied fatigue criterion, thickness of concrete slab, standard and actual axle loads, and for most methods varies from 4 to 16. The French criterion gives constant exponent $n = 16$. The new AASHTO 2004 criterion gives $n > 20$.

The important factor that influences axle load equivalency is the form of the fatigue criterion itself. The second important factor is thickness of the slab. Axle load aggressiveness, indicated by exponent n, is greater for thinner slabs. The effect of the modulus of subgrade reaction is less significant, however greater traffic aggressiveness was noticed for lower slab support.

The main conclusion from this study is that the axle load equivalency factors should be related to applied fatigue criteria. If the design traffic is calculated with use of the "fourth power equation" and after that any selected fatigue criterion is applied in mechanistic-empirical analysis of rigid pavement the results of the design could be erroneous. The axle factors and consequently the number of equivalent axle loads change for the same real traffic if different fatigue law is applied in analysis. The proper approach in the design should be such that after selection of the fatigue criterion for rigid pavement design the method of calculation of equivalency axle load factors should be respectively adjusted. It is important that the fatigue criteria and the load equivalency factors should be interrelated. The presented method of analysis can be used for any other fatigue criteria applied in design of rigid pavements.

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