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Effect of pavement roughness and vehicle dynamic loads on decrease of fatigue life of flexible pavements

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Abstract

Due to the fact that pavement surfaces are not ideally even, dynamic loads of vehicle axles deviate from static loads. Higher dynamic loads contribute to faster pavement distress. The distribution of dynamic loads is similar to normal distribution and can be described by static load and factors DI (dynamic impact) and DLC (dynamic load coefficient). With the deterioration of pavement condition its evenness decreases as well and the roughness index IRI increases. The maximum dynamic loads increase and their detrimental effect on pavement structure increases. The main objective of the paper is to assess how dynamic loads caused by pavement roughness affect pavement distress. In the article a new measure – the coefficient of pavement dynamic susceptibility DSC has been introduced. The coefficient DSC expresses the absolute increase in equivalent axle load factor caused by dynamic load effects. It was shown that with the increase in roughness from IRI = 1.0 mm/m (which is the value measured for new properly constructed pavements) to IRI = 2.0 mm/m, the coefficient DSC increases by up to 8%. Further deterioration of roughness to IRI = 4.0 mm/m causes increase of DSC by up to 32%. In consequence of increase of coefficient DSC the fatigue life of pavement structure decreases by 5.5% for IRI = 2mm/m and by 23% for IRI = 4 mm/m. It means that low initial roughness of pavement structure gained by high quality of road construction and proper maintenance of pavement during service will reduce pavement distress and increase its service life.

Keywords: vehicle dynamic loads, equivalent axle load factor, International Roughness Index, pavement fatigue life, dynamic impact, dynamic load coefficient

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Nomenclature

DLC	Dynamic Load Coefficient
DI	Dynamic Impact
DSC	Dynamic Susceptibility Coefficient
IRI	International Roughness Index
V	average commercial vehicles speed
σ	standard deviation of axle loading force
$\bar{F}$	mean value of axle loading force
Zr	quantile of the normal distribution
F_{dyn}	vehicle load equivalency factor incorporating the dynamic effect
Qstat	force of static axle load
Qdyn	force of dynamic axle load
Qs	standard axle load equal to 100 kN

1. Introduction

1.1. Outline of the problem

Pavement evenness is directly related to dynamics of vehicle movement. Due to roughness of pavement, the loads from moving vehicle axles vary from static loads. Dynamic loading from vehicles results in higher stress values in pavement structure as well as bridges and elements of road infrastructure. Results of measurements of dynamic axle loads were performed by Gilespie et al. (1992) and Cebon (1999). According to research carried out by Gilespie at al. (1992) for such probability distributions the expected value is usually equal to static load value. The Dynamic Load Coefficient (DLC) is a coefficient of variability of dynamic loading and is a measure that characterizes the probability distribution of dynamic axle loads. It is expressed as:

$$DLC = \frac{\sigma}{\bar{F}} \quad (1)$$

where: σ – standard deviation of axle loading force, $\bar{F}$ – mean value of axle loading force, approximately equal to static loading.
There is another measure of dynamic axle loading used in literature: the Dynamic Impact Factor (DI), given by:

$$DI = 1 + Z_r DLC \quad (2)$$

where: Zr – quantile of the normal distribution.
An increase in DLC and DI is correlated with an increase in the maximum dynamic pavement loading from the vehicle. The values of DLC and DI are affected by suspension characteristics, vehicle speed and pavement evenness.

In research conducted by Gillespie et al. (1992) an analysis of impact of suspension type on life of flexible pavements proved that vehicles with conventional suspension (leaf springs) inflict greater damage in terms of fatigue cracking than vehicles with air suspension. In terms of permanent deformation, the impact of suspension type and dynamic loading is negligible. Influence of suspension type was analyzed within the DIVINE project (OECD, 1998) as well, which showed that pavements subjected to loading with vehicles with conventional suspension show distress after a period of time 15% shorter than those subjected to loading with vehicles with air suspension.

Sweatman (1983) researched the impact of pavement evenness and vehicle speed on DLC coefficient for various vehicle suspension systems. The results imply that DLC increases with vehicle speed. This conclusion is supported by research of Gillespie et al. (1992). Literature study (Bilodeau et al. 2015, Cebon 1999, Gilespie 1992, Misaghi et al. 2010, Shi and Cai 2009, Sweatman 1983) shows that with decrease in evenness (increase in IRI index) the DLC and DI increase, that is: the dynamic loading from vehicle axles increases. The assessment of relationship between IRI and factors DLC and DI were performed by Misaghi et al. (2010) and Bilodeau et al. (2015).

The state and parameters of vehicle suspension, though significant in terms of dynamic loading, are practically impossible to control on the road. Imposing a speed limit with dynamic interactions in mind would not prove effective, as for lower vehicle speeds the stiffness moduli of the asphalt layers decrease and the pavement responds with greater strain. The only parameter that is both controllable and significant in terms of dynamic loading is the pavement evenness. Proper evenness of new roads is achieved by constructing the pavement with due diligence. Evenness is a factor that is not related to additional costs in the project, while it may significantly increase the service life of the pavement or reduce the risk of premature failure by reducing the dynamic loads exerted by vehicles.

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1.2. Objective of the article

The objective of this article is to assess the impact of heavy vehicle dynamic loading resulting from pavement roughness (measured with IRI index) on load equivalency factors used for pavement design and further to assess decrease of fatigue life of flexible pavements as an effect of dynamic loads.

2. Impact of pavement evenness and vehicle speed on dynamic loading from vehicles

2.1. Road evenness conditions in Poland

Longitudinal road evenness is measured with IRI index (International Roughness Index). In guidelines concerning the use of Pavement State Diagnostics system (GDDKiA, 2015) requirements were set for road evenness and shown in the legend in Figure 1.

The latest results gathered for the technical state of pavements (2015) concerning longitudinal evenness show that on national roads 75% of length of sections are in good state (condition class A) and 22% in satisfactory state. Less than 4% of sections are in unsatisfactory or bad condition Radzikowski (2016). The state of evenness of national roads in Poland is summarized in Figure 1. For several years the evenness of national roads has been improving due to rehabilitation and new projects. It is undeniable that the state of evenness of provincial, district and communal roads is inferior, but there is no data available from evenness measurements for those roads.

According to the ordinance of the Minister of Infrastructure and Development traffic lanes of new pavements shall show an average IRI index of:

- IRI_{avg} = 1.3 for road classes A (motorway),S (expressway) and GP (high-speed main road),
- IRI_{avg} = 1.7 for road class G (main road).

For roads falling into classes lower than G no requirements concerning IRI were set. It is worth noting that the ordinance allows the maximum measured IRI value of:

- IRI_{max} = 2.4 for road classes A,S and GP,
- IRI_{max} = 3.4 for road class G.

This means that on new roads occurrence of local decrease in evenness relative to the rest of the section is accepted. In such locations the dynamic impact of vehicles are greater, resulting in faster pavement deterioration, as will be shown in the following part of the article.

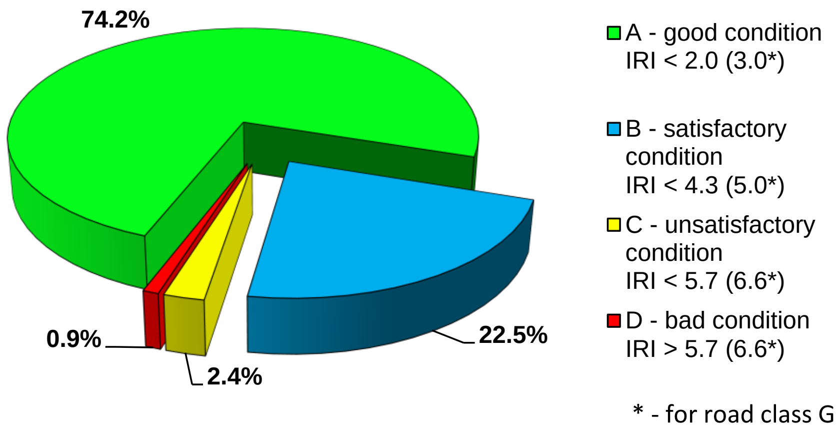

Fig. 1. State of pavement evenness of national roads in Poland in 2015 (Radzikowski, 2016)

2.2. Heavy vehicles speed

Speed of vehicles, similarly to pavement evenness, significantly affects the dynamic loading as well as values of DI and DLC. Typical permissible heavy vehicle speed in Poland outside built-up areas is 70 km/h on single-carriageways with two lanes and 80 km/h on dual carriageways, including expressways and motorways. Based on continuous measurements of traffic speed, it may be assumed that the average speed of heavy vehicles on motorways and expressways is 90 km/h and on other roads 70 km/h Judycki et a. (2014), Rys et al. (2016).

2.3. Pavement dynamic susceptibility coefficient

The analyses presented in this article are based on American models of dynamic heavy vehicle loading described in the report Misaghi S, (2010). The correlation between DI factor and vehicle speed and pavement evenness was expressed with the following model:

$$DI = 1 + \alpha \cdot V \cdot IRI \tag{3}$$

in which: $\alpha = 0{,}0017$ – parameter for the "quarter car" model which was assumed in the analysis, V – average vehicle speed [km/h], IRI – International Roughness Index [mm/m].

The values of dynamic load coefficient (DLC) were calculated from dynamic impact factor DI by transformation of relationship (2):

$$DLC = \frac{DI - 1}{Zr} = \frac{\sigma}{\text{Qstat}} \tag{4}$$

in which: DI – dynamic impact factor according to model (3), Zr – quantile of normal distribution, Zr = 2, Qstat – force of static axle load, approximately equal to mean value of dynamic loads, σ – standard deviation of dynamic axle loads.
The distribution of dynamic axle loads can be defined by static load Qstat and one of the measures: DI or DLC. Using the fourth power formula, the values of dynamic loading forces were transformed into equivalency factors that are a measure of vehicle impact on the structure. The average equivalency factor for dynamic axle loading was calculated in a discrete manner, based on the probability density function for normal distribution of dynamic axle loads, using:

$$F_{dyn} = \sum_{i=1}^{n} \left(\frac{Qdyn_i}{Q_s}\right)^4 p_i \tag{5}$$

in which: F_{dyn} – vehicle load equivalency factor incorporating the dynamic effect, $Qdyn_i$ – dynamic load of i-th axle, occurring with a given probability p_i, with the reservation that the sum is calculated up to a certain significance level α ($p < \alpha$), Q_s – standard axle load, Q_s = 100 kN, n – the number of assumed ranges of dynamic loading within the significance level α.
A chart representing the calculation of dynamic load equivalency factor is shown in Figure 3. A standard axle load of 100 kN was used in the example. The force of 100 kN reflects the static load. When the vehicle is in

motion, the dynamic loading force changes due to pavement roughness – the distribution in marked with a blue solid line in Figure 2. In the example shown the assumed value of dynamic load coefficient was DLC = 0.1 and the dynamic impact factor was DI = 1.2. The maximum dynamic axle load is 120 kN and the minimum is 80 kN (at significance level $\alpha = 96\%$). The variable dynamic loads from vehicles have different impact on the structure – this impact is described by the function of axle load equivalency factor, which was plotted with a red dotted line in Figure 2. It is assumed that for flexible pavements this function represents the fourth power relationship. As it was proved in work of Judycki (2010), fourth power equation provides similar load equivalency factors for flexible pavements as load equivalency factors determined on the basis of fatigue criteria. The product of dynamic load probability distribution function with the axle load equivalency factor function is the mean dynamic load equivalency factor. In the example described its value is 1.06, while the factor without incorporation of dynamic effects is equal to 1.00. The mean dynamic load equivalency factor divided by the static load equivalency factor gives the pavement Dynamic Susceptibility Coefficient DSC (7). Transformation (6) shows that the coefficient DSC is independent of the static axle load and may be used regardless of magnitude of axle loads.

$$F_{dyn} = \sum_{i=1}^{n} \left(\frac{Qdyn_i}{Q_s}\right)^4 p_i = \sum_{i=1}^{n} \left(\frac{Qstat + \mu_i \cdot DLC \cdot Qstat}{Q_s}\right)^4 p_i = \\ = \left(\frac{Qstat}{Qs}\right)^4 \cdot \sum_{i=1}^{n} (1 + \mu_i \cdot DLC)^4 p_i = DSC \left(\frac{Qstat}{Qs}\right)^4 \tag{6}$$

$$DSC = \sum_{i=1}^{n} (1 + \mu_i \cdot DLC)^4 p_i \tag{7}$$

in which: μ_i – quantile of normal distribution for a given probability p_i, which may take on both positive and negative values, while $(p < \alpha)$, where α is the assumed significance level (in the above example $\alpha = 96\%$), DSC – the pavement dynamic susceptibility coefficient, other symbols as described above. It should be noted that the coefficient DSC in equation (6) is dependent on the dynamic load coefficient DLC and the assumed significance level α, and not on the load of given axle.

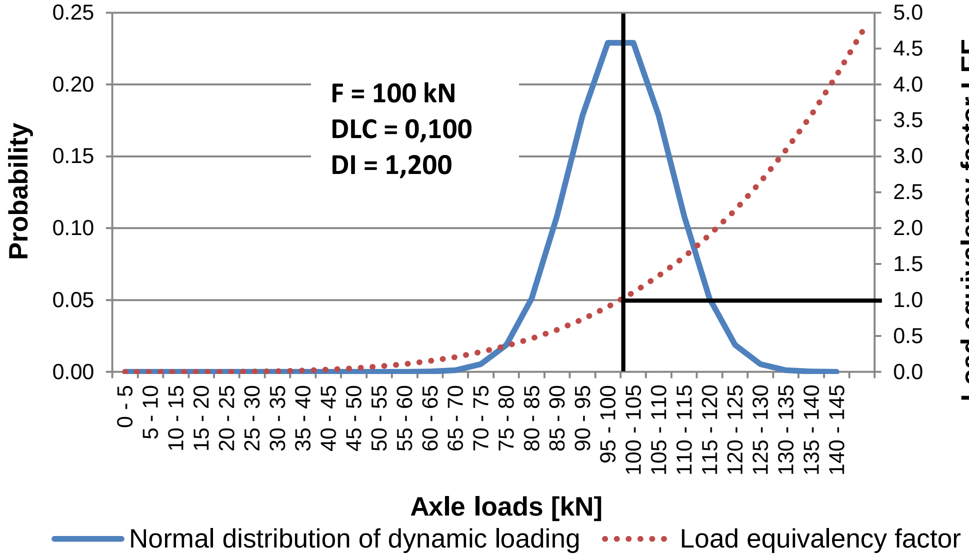

Fig. 2. Graphical representation of calculation of average dynamic load equivalency factor

3. Analysis of the impact of surface evenness and vehicle speed on pavement life

Based on equations (6) and (3), a relationship between IRI index and the pavement dynamic susceptibility coefficient DSC was derived for four chosen values of average heavy vehicle speed. The results are presented in Fig. 3A.

The impact of dynamic vehicle loads on reduction of pavement fatigue life was described using the Decrease of Fatigue Life (DFL) factor introduced by Rys et al. (2016) and transformed in the following manner for the purposes of this article:

$$DFL\ (\%) = \left(1 - \frac{F_{dyn,IRIp}}{F_{dyn,IRI}}\right) = \left(1 - \frac{DSC_{IRI\ ref} \cdot F_{stat}}{DSC_{IRI} \cdot F_{stat}}\right) = \left(1 - \frac{DSC_{IRI\ ref}}{DSC_{IRI}}\right) \qquad (8)$$

in which: $F_{dyn,IRIp}$, $F_{dyn,IRI}$ – dynamic axle load equivalency factors for pavement roughness IRIp and IRI respectively, F_{stat} – static axle load equivalency factor, DSC $_{IRI,\ ref}$, DSC $_{IRI}$ – pavement dynamic susceptibility coefficient for pavement roughness IRI_{ref} and IRI respectively, IRI_{ref} – reference value of International Roughness Index (IRI_{ref} = 2.0 was assumed), IRI – actual average International Roughness Index.

The DFL factor describes the relative decrease (in percent) in pavement fatigue life after a decrease in evenness, as compared to a reference pavement with proper evenness. Reference evenness of IRIp = 2.0 [mm/m] was assumed as the limiting value of the evenness condition class A (good) for motorways. If a different reference level is assumed (e.g. IRI_{ref} = 1.0 [mm/m]) the DFL factor increases by several percent. The relationship between DFL and IRI is shown in Fig. 3B.

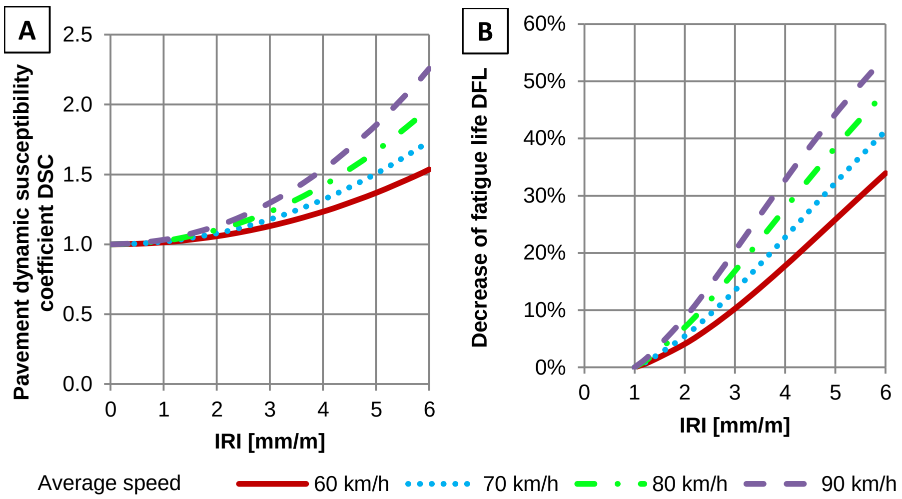

Fig. 4. The impact of pavement evenness and vehicle speed on A) pavement dynamic susceptibility coefficient DSC B) decrease in pavement fatigue life

For very even pavements (IRI ≤ 1 mm/m) the DSC is close to 1 and increases significantly (Fig. 4A) with deterioration of evenness (increase in IRI). This means that for very even pavements the impact of loading with incorporation of dynamic effects is the same as the impact of static loading. With the reduction of evenness the pavement is put under greater strain due to dynamic loading from vehicles. It is worth noting that during service of pavement its evenness gradually deteriorates, which in turn results in greater dynamic loads and further acceleration in reduction of pavement life.

According to polish requirements, the maximum acceptable IRI value for new roads is 1.3 mm/m for classes A, S and GP and 1.7 mm/m for class G. Requirements for lower road classes have not been defined. In practice the maximum achievable evenness is at the level of IRI ≈ 1.0. A change of roughness within the acceptable limits for respective classes (i.e. from IRI = 1.0 to IRI = 2.0 [mm/m] for classes A, S and GP, and from IRI = 1.0 to IRI = 3.0 [mm/m] for road class G) results in an increase in pavement dynamic susceptibility coefficient DSC respectively from DSC = 1.03 to DSC = 1.13, that is by 9% (road classes A, S, GP) and from DSC = 1.02 to

DSC = 1.18, that is by 16% (road class G). Ensuring high initial evenness of pavement considerably lengthens its fatigue life and is particularly important when high values of vehicle speed are expected, i.e. on motorways and expressways.

Figure 3B shows that when a pavement degrades to the limit of satisfactory evenness condition (class B), the fatigue life is reduced by as much as 30%. A degradation in evenness class means a change in IRI from 2.0 to 4.3 [mm/m] for roads A, S and GP and vehicle speed of v = 90 km/h, and from 2.0 to 5.0 [mm/m] for roads of class G and vehicle speed of v = 70 km. This correlation demonstrates the importance of evenness in terms of service life of the whole pavement structure. Loss of evenness will considerably shorten the fatigue life, whereas maintaining proper pavement evenness during service will greatly reduce the rate of its deterioration.

4. Summary

- Dynamic loads exerted by vehicle axles on pavement have a normal distribution in which the expected value is equal to static load and standard deviation depends on such factors as pavement roughness, vehicle speed and suspension parameters.
- According to literature, assessment of variability of dynamic axle loads is performed with the use of the following values: DI (dynamic impact) or DLC (dynamic load coefficient). DI and DLC characterize only the dynamic loading and not its impact on the pavement. An increase in DI or DLC corresponds with an increase in maximum values of vehicle axle loading, and only consequently with greater impact of the vehicle on pavement.
- In order to describe the dynamic load impact on pavement, the distribution of dynamic axle loads was taken into account, which is characterized by DI or DLC and by function of axle load equivalency factor. Derivation of pavement dynamic susceptibility coefficient DSC was presented.
- Pavement dynamic susceptibility coefficient DSC is considerably correlated with pavement roughness. A decrease in pavement evenness, represented by a change in IRI to 2.0 (satisfactory conditions according to polish requirements) results in an increase in pavement dynamic susceptibility coefficient DSC by 9%. Further deterioration of evenness to 4.3 (unsatisfactory condition) results in a decrease in fatigue life by as much as 30%. This means that ensuring proper initial evenness and its maintenance throughout service life may considerably lengthen the fatigue life of the pavement structure.

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