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Analysis of effect of overloaded vehicles on fatigue life of flexible pavements based on weigh in motion (WIM) data

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Overloaded vehicles have a significant impact on pavement fatigue life and distress. As the studies show, the phenomena intensify when the control of traffic is poor. The paper presents the results of the research including analysis of weigh in motion data from eight stations and analysis of asphalt pavement fatigue caused by mixed traffic. Distributions of vehicles axles load including the multiple axles effects are presented. Mixed axle loads were transformed into equivalent number of standard 100 kN axle loads. The regression model of load equivalency factor depending on the axle load distribution and the percentage of overloaded vehicles is presented. The analysis of the effect of overloaded vehicles on decrease of fatigue life of a pavement structure is presented. The analysis has shown that the increase of percentage of overloaded vehicles from 0% to 20% can reduce the fatigue life of asphalt pavement upto 50%.

Keywords: overloaded vehicles; overweight vehicles; axle loads distribution; fatigue life; fatigue criteria; fatigue cracking; equivalent axle load factor; load equivalency factor; flexible pavement

Introduction

Background

In Poland, after economic transformation in the early 1990s road transport has rapidly grown. The vehicle class distribution has changed significantly and trailer trucks became much more common. After accession of Poland to the European Union in 2005 the maximum legal weights have increased and, as a consequence, vehicles axle loads have also increased. Moreover, some parts of vehicles exceed the maximum legal loads. Due to recent growth of road transport, overloaded vehicles have become a serious problem in Poland (Szydlo and Wardega 2003, Rys *et al.* 2011). Thus, the studies of the overloaded vehicles impact on pavement distress were necessary to be carried out.

There have been past studies of overloading and their effects on pavements (Mohammadi and Shah 1992, Sadeghi and Fathli 2007, Pais *et al.* 2013). These and other studies indicate that vehicle overloading and their damage potentials may substantially reduce the service life of road pavements. The simplest statistic to describe overloading is the percentage of overloaded vehicles in the total number of trucks. In certain countries, such as China or Indonesia, it was revealed that the percentage of overloaded vehicles can reach extremely high level of 80% (Mulyono and Antameng 2010, Zhao *et al.* 2012) but more often the percentage of overloaded vehicles is in the range from 10% to 30%. Nevertheless in certain vehicle classes, such as five- or six-axle single-trailer trucks, the percentage of overloaded vehicles is particularly high and can gain approximately 40% (Mohammadi and Shah 1992, Pais *et al.* 2013). Compared with properly loaded vehicles, overloaded vehicles occur less frequently but due to their greater potential to cause damage they may significantly contribute to the distress of pavement. Faster pavement distress causes increase of maintenance costs and more frequent repairs. Studies by Pais *et al.* (2013) revealed that maintenance cost of road calculated per one vehicle is higher by 100% for overloaded vehicles compared to the cost of the same vehicle with legal loads.

However, the pavement distress depends not only on the percentage of overloaded vehicles but also on the probability distributions for vehicle loads greater than the legal load limit (Mohammadi and Shah 1992). This information is expressed by gross weight distribution or by axle load distribution. Axle load distribution is crucial in estimating the effects of actual traffic on pavement response and distress in mechanistic-empirical approach and it is closely related with the percentage of overloaded vehicles (Zhao *et al.* 2012). According to Zhao *et al.* (2012), among the three types of pavement distress: rutting, bottom–up and top–down fatigue cracking, rutting is the least sensitive to the variations in axle load distribution so consequently least sensitive to the variations in the percentage of overloaded vehicles. However, studies by De Beer *et al.* (1997, 2002) have shown that overloaded axles cause significant non-uniformity of tyre contact stress that results in increase of plastic deformation of asphalt mixes. Besides, pavement

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condition has an impact on pavement vulnerability to damage (Scott and Ferrara 2011).

Overloaded vehicles also cause faster bridge damage. According to Jacob and Labry (2002), the increase of 15% of a vehicle gross weight may lead to doubling the bridge fatigue damage, and thus reduce the lifetime of the structure by a factor of 2. Vehicle overloading also has negative impact on road safety due to longer stopping distance during emergency braking and poor technical condition of frequently overloading vehicles (Turner *et al.* 2008).

The percentage of overloaded vehicles can be reduced by regular vehicle control and high enforcement level. The weigh in motion (WIM) system allows to improve vehicle control and it is developing intensively in Europe (Jacob and Loo 2008). The system enables to check most of trucks in traffic flow and identify those which are overloaded. The impact of enforcement level on the percentage of overloaded vehicles has been studied by Tailor *et al.* (2000), and the result showed that the overloaded vehicles level is about 20–30% when there is no enforcement while high enforcement level can decrease the overloaded vehicles level from 1% to 2%.However, higher enforcement level results in shifting of the freight that was being moved on overloaded vehicles onto vehicles loaded with accordance to regulations (Stephens *et al.* 2003). However, according to Stephens *et al.* (2003) approach, much less pavement damage is incurred in carrying freight on more vehicles that operate legally in comparison with carrying the same freight on fewer vehicles than operate over weight. This statement results from the fact that the damaging effect of axle increases with relative increase of its load to the power four.

Objectives

The objectives of this paper are to develop the model of fatigue life depending on the percentage of overloaded vehicles and axle load distribution to: (1) reveal how much the overloaded vehicles influence on pavement structure distress and (2) how much the pavement fatigue life decreases as a result of overloading.

Measurement of heavy traffic

Collecting and verification of data from weigh in motion (WIM)

The main task of WIM devices is to weigh and measure all vehicles moving in traffic and identify those that are suspected to be overloaded and to direct them to accurate inspection on static weigh. In Poland, only static weigh can be the legal basis to impose a fine. Data from WIM stations are collected and saved, so they can be used for statistical analysis of traffic. In this paper, data from eight WIM stations installed on Polish national roads and on one motorway. Localizations of stations are shown in the Figure 1. There are two systems of weight sensors used in considered WIM stations: plate sensors PAT DAW 100® (Stations A2 and DK11) and piezo-electric quartz Kistler

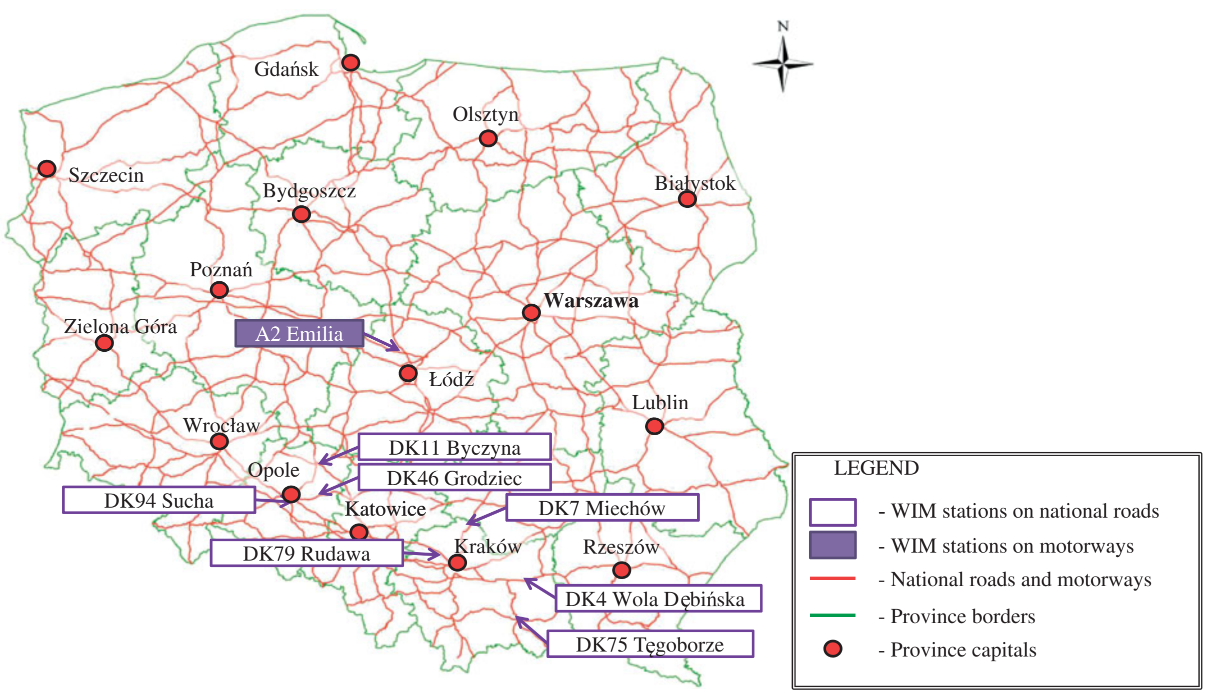

Figure 1. Localizations of WIM stations on roads in Poland considered in the analysis.

Lineas® sensors (other stations). Cameras and induction loops are also mounted in all stations. The WIM stations can be classified as a class B7 according to COST 323 WIM classification (Jacob 2002).

The data considered in this study were collected since September 2009 till May 2013. The total operating time of each WIM station was different but not shorter than 5 months. The raw WIM data had to be verified before further processing. The first step of data verification was to check if successive days include complete number of measuring hours. Days that included some gaps in weighing of vehicles were rejected. In the next step, the data were verified using series of filters based on studies of *WIM Data Analyst Manual* (FHWA 2010) and NCHRP report 538 (NCHRP 2005) and vehicle technical parameters review. The filtering process focused on identifying and removing invalid records from the database and choosing only trucks for further analysis. Vehicle records were discarded when:

- Vehicle gross weight was lower than 35 kN;
- Axles loads were lower than 5 kN or greater than 200 kN;
- Vehicle length was lower than 3 m or greater than 20 m;
- Gaps between neighbouring axles were lower than 0.5 m;
- Vehicle speed was lower than 5 km/h or higher than 180 km/h;
- Record was uncompleted or flagged with the WIM system error.

In Table 1, the time of measurement and total number of records used in the analysis are given for each WIM station. To sum up, more than 39 million of all types of vehicles were recorded, including cars, vans etc., of which more than 8.5 million records of trucks were used in the analysis.

Overloaded vehicle flow

The basis to classify a vehicle as overloaded was the European Union Council Directive 96/53/EC (1996). The percentage of overloaded vehicles (abbreviated further as OV) was calculated for each station. Each vehicle was checked and marked if overloaded using the in-house software developed specifically for this study at the Gdansk University of Technology. A vehicle was treated as overloaded in the following cases:

- The vehicle gross weight was greater than the legal limit;
- The load of a single or tandem or tridem axle was greater than legal limit;
- Both the gross weight and the axle load were greater than legal limits.

The legal limit of vehicle gross weight depends on the class of the vehicle, for example, for two-axle single truck unit it is equal to 18,000 kg and for five-axle truck with semi-trailer it is equal to 40,000 kg. The legal limit of axle loads depends on the type of the axle (steering, drive etc.), the distance to neighbouring axles and the suspension type. For example, for single drive axles the maximum axle load equals to 115 kN and for the rest types of single axles it is equal to 100 kN.

The percentages of overloaded vehicles for each WIM station are presented in Figure 2. As seen in Figure 2, the

Table 1. Time of WIM measurement and number of vehicles records used in analysis.

WIM station (road no/location)		Traffic direction	Time of measurements: Days	Time of measurements: Time period	Total number of records: Raw WIM records of all vehicles types	Total number of records: Records of trucks (after data verification)
A2	Emilia	E	621	January 2011–December 2012	6,247,706	2,580,957
		W				
DK4	Wola Debinska	W	822	July 2010–December 2012	14,472,484	2,680,110
		E	530	July 2010–December 2010 November 2011–December 2012		
DK7	Miechow	S	271	January 2012–December 2012	4,223,376	537,063
		N	362			
DK11	Byczyna	S	1064	September 2009– December 2012	3,016,440	811,792
DK46	Grodziec	W	705	January 2011–December 2012	4,712,036	1,042,455
		E	716			
DK75	Tegoborze	S	213	January 2012–December 2012	3,488,177	390,778
		N	296			
DK79	Rudawa	W	129	January 2013–May 2013	1,575,527	179,281
		E	122			
DK94	Sucha	W	107	January 2013–May 2013	992,640	153,673
		E	128			
Total					39,822,957	8,518,913

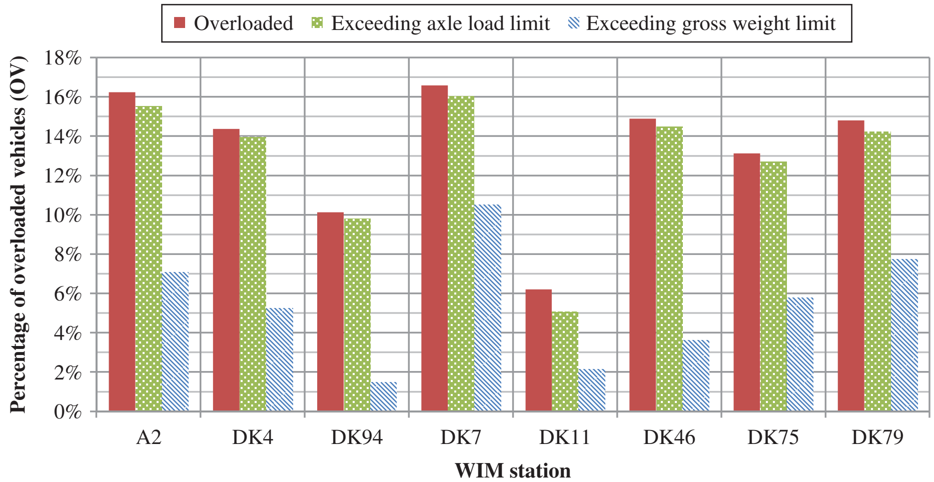

Figure 2. Percentage of overloaded vehicles OV in selected WIM stations in Poland.

percentage of overloaded vehicles varies and ranges from 6% to 16.5%. The level of enforcement has significant impact on this statistics. It is known from the site interview that the continuous control is performed on DK11 (the highest enforcement level) where the percentage of overloaded vehicles is the lowest, on the rest of WIM stations the control is temporary. Most of overloaded vehicles exceed their axle load limit, whereas the gross weight is exceeded less frequently.

Axle load distribution and the effect of multiple axles

Axle loads distributions characterise traffic load conditions and most often they are prepared separately for single, tandem and tridem axles, due to stress and strains overlap caused by short distance between neighbouring axles in tandem and tridem. The data from Polish WIM stations indicated that the distance between axles in tandem and tridem axles in more than 80% ranges from 1.2 m to 1.4 m. The distance between neighbouring axles has a significant impact on the fatigue cracking of asphalt layers (Homsi *et al.* 2011, 2012). However, there are several different methods to calculate the fatigue cracking caused by passes of tandem and tridem axles by the use of fatigue criteria. These methods are required to calculate the pavement response under tandem and tridem axles. The response can be expressed as peak strains, peak-midway strain or dissipated energy. All of these methods give different results. The conclusion of past studies of multiple axle effects on pavement, which were carried out by Gillespie *et al.* (1992), Chatti and Mohtar (2004) and Chatti *et al.* (2009), is that tandem and tridem axles tend to cause less cracking than single axles. This statement is confirmed by the results of full scale pavement tests carried by Homsi *et al.* (2012). According to Salama *et al.* (2006), the best way to assess the damage caused by multiple axle configurations is field measurements. However in some pavement design manuals, for example in German RSTO 12 (FGSV 2012), the multiple axle loads effect are treated as effects of loads of each individual axles, excluding the impact of the distance between neighbouring axles.

In this paper, the following simplified approach was used. All multiple axles loads, tandem and tridem, were converted into *representative single-axle loads* having assumed the same damaging effect to the pavement structure. The conversion was based on the fourth power formula as a simplification of AASHTO equations (AASHTO 1993). For each WIM site three distributions of single, tandem and tridem axles were replaced by one equivalent distribution of single-axle loads. To determine the representative single-axle loads for the actual tandem and tridem axle loads, the fourth power equation was transformed as follows:

$$F_j = \left(\frac{Q_{\mathrm{I}}}{100}\right)^n = \left(\frac{Q_{\mathrm{II}}}{184}\right)^n \quad \text{for tandem axle} \tag{1a}$$

$$F_j = \left(\frac{Q_{\mathrm{I}}}{100}\right)^n = \left(\frac{Q_{\mathrm{III}}}{263}\right)^n \quad \text{for tridem axle} \tag{1b}$$

where F_j is equivalent axle load factor, Q_{I} is representative single-axle load equivalent to actual tandem or tridem axle loads [kN], Q_{II} is the actual tandem axle load (sum of two component axles loads) [kN], Q_{III} is the actual tridem axle load (sum of three component axles loads) [kN] and n means exponent equal to 4. The loads of 184 kN and 263 kN, used in the denominators of Equations (1a) and (1b), were calculated from the AASHTO (1993) equations for terminal level of serviceability $p_t = 2.5$ and structure number SN = 5.15 as loads for tandem or tridem axles which are equivalent to standard axle load 100 kN (Judycki

2006, 2010). To form a uniform distribution of equivalent single-axle loads, for each WIM station, all tandem and tridem axle loads (Q_{II} and Q_{III}) were converted into representative single-axle loads Q_{I} calculated from the following equations:

$$Q_{\mathrm{I}} = \frac{100}{184} \times Q_{\mathrm{II}} = 0.543 \times Q_{\mathrm{II}} \quad \text{for tandem axle} \qquad (2a)$$

$$Q_{\mathrm{I}} = \frac{100}{263} \times Q_{\mathrm{III}} = 0.380 \times Q_{\mathrm{III}} \quad \text{for tridem axle} \qquad (2b)$$

For each of the WIM station, tandem and tridem axles were replaced by representative single axles. The distributions of representative single-axle loads were prepared for all WIM sites, and they are given in Figure 3. The distributions of representative single-axle loads are the sum of distribution of single-axle loads, distribution of tandem representative loads (converted by Equation (2a)) and distribution of tridem representative loads (converted by Equation (2b)).

It can be seen that distribution can be unimodal (Figure 3a) or in most cases bimodal (Figure 3b). The proportion between heavier and lighter representative axles varies for different WIM stations, and also the percentage of the heaviest representative axles is different. Therefore, it can be generally stated that the axle load distribution characterises the specific traffic condition at a given WIM station.

Calculations of the impact of overloaded vehicles on pavement fatigue life

Load equivalency factor

Load Equivalency Factor (LEF) characterises the damaging effect of a given flow of trucks to pavement structure. It varies in relation to the distribution of axle loads on a given road. Assuming that for a given flow of trucks all multiple axle loads were converted into representative single-axle loads the LEF can be defined as follows:

$$N_{100} = \mathrm{LEF} \times N_{\mathrm{axle}} \qquad (3)$$

where, N_{100} denotes traffic expressed in a number of standard equivalent axle loads 100 kN, LEF denotes load equivalency factor and N_{axle} denotes the number of representative single-axle loads in a given flow of trucks.

In other words, the LEF can be defined as the number of passes of the equivalent standard axle loads 100 kN that induces the same damaging effect to a given pavement

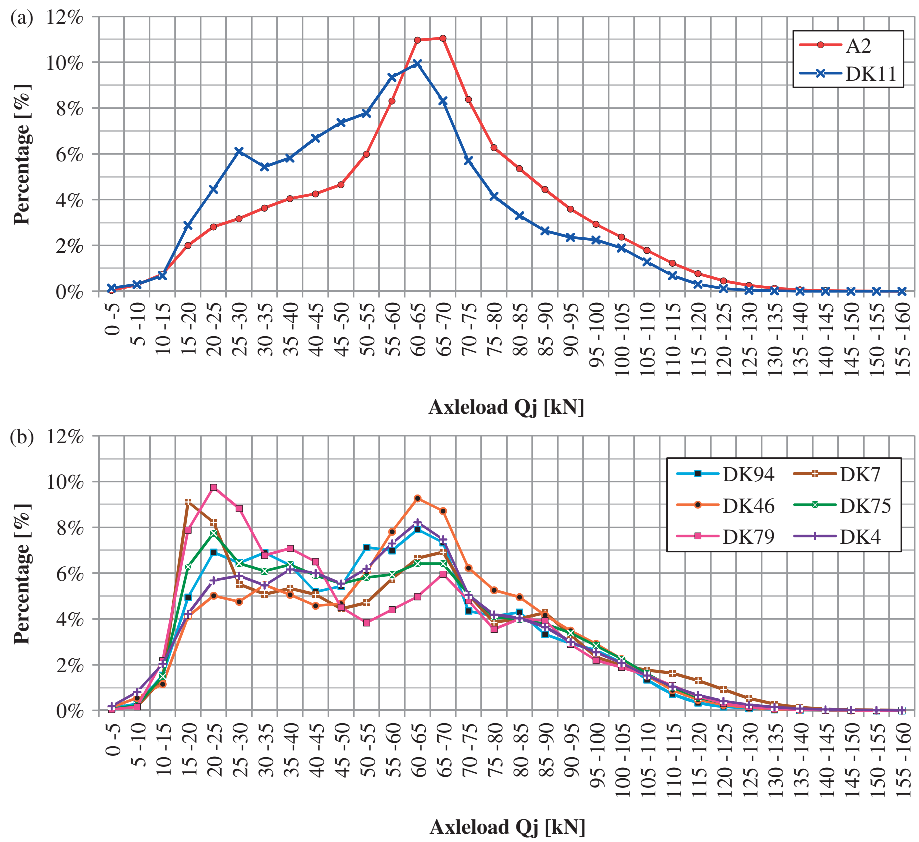

Figure 3. Distributions of representative single-axle loads for all WIM sites: (a) unimodal, (b) bimodal.

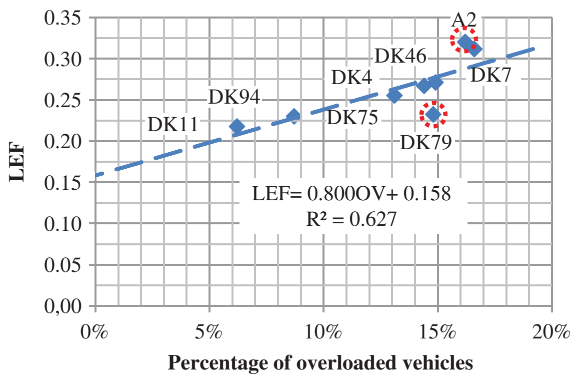

Figure 4. Load Equivalency Factor (LEF) in relation to percentage of overloaded vehicles OV.

structure as one pass of an average representative single-axle load in a given flow of trucks. The LEF can be calculated from the following formula:

$$\mathrm{LEF} = \sum_{j=1}^{m} F_j p_j \tag{4}$$

where LEF denotes load equivalency factor for a given WIM station, F_j is equivalent axle load factor as a function of axle load Q_j, p_j is the percentage of j axles taken from the axle load distribution for a given WIM station (Figure 3), j denotes number of axle load interval and m denotes total number of axles load intervals.

The equivalent axle load factors were calculated with use of the simplified fourth power equation:

$$F_j = \left(\frac{Q_j}{Q_s}\right)^4 \tag{5}$$

where Q_j is actual single-axle load, kN and Q_s is standard single-axle load 100 kN.

Regression model for LEF in relation to the percentage of overloaded vehicles OV and axle load distribution

At first step, the linear correlation of LEF with the percentage of overloaded vehicles OV was determined, and it was given in Figure 4.

It was found that the coefficient of determination for the linear relationship LEF(OV) was low ($R^2 = 0.627$) and the relationship was rather weak (Figure 4). Especially, A2 and DK79 differ from the regression line (see encircled points in Figure 4).

It can be concluded from the test data that not only the percentage of overloaded vehicles OV but also the character of the representative single-axle load distribution (see Figure 3) affects the LEF. Therefore, the following regression model was proposed:

$$\mathrm{LEF} = a_1X_1 + a_2X_2 + a_3X_3 + a_4\mathrm{OV}. \tag{6}$$

where a_1, a_2, a_3, a_4 are regression model factors, X_1 is percentage of representative single axles $Q_j < 30\,\mathrm{kN}$ (below 30 kN), X_2 is percentage of representative single axles $30\,\mathrm{kN} \le Q_j < 60\,\mathrm{kN}$, X_3 is percentage of representative single axles $60\,\mathrm{kN} \le Q_j < 90\,\mathrm{kN}$ and OV is percentage of overloaded vehicles. The values X_1, X_2, X_3 of Equation (6) are calculated as a field area under the distribution line and are shown in Figure 5 as an example for roads DK 79 and A2. The percentage X_4 of representative axles of load $Q_j \ge 90\,\mathrm{kN}$ is also shown in Figure 5. However, the variable X_4 is excluded from regression equation because it is precisely defined by the other variables X_1, X_2, X_3 as $X_4 = 100\% - (X_1 + X_2 + X_3)$. Also it was found in the analysis that the percentage of representative axles X_4 and the percentage of overloaded vehicles OV are linearly correlated, with $R^2 > 0.75$. Table 2 presents the data on the representative single-axle load distribution characteristics X_1, X_2, X_3, X_4 and percentage of overloaded vehicles OV for each tested road.

Regression model coefficients are given in Table 3 and indicate that its accuracy is very good. The graphical interpretation of the model is given in Figure 6 which presents calculated values of the LEF for each considered road and assumed different levels of overloaded vehicles. The lines are parallel that results from the nature of regression (Equation (6)). The slope of all lines is the same for each road and equals to a_4. The positions of LEF(OV) lines for each investigated road are dependent on the axle load distribution, as shown in Figure 2, which are characterized by factors X_1, X_2 and X_3.

The relative increase of load equivalency factor (LEF) and decrease of fatigue life (DFL) of pavement structures caused by overloaded vehicles

The relative increase of LEF is presented in Figure 7(a) and was calculated as:

$$\text{Relative increase of LEF (\%)} = \frac{\mathrm{LEF}_{\mathrm{OV}} - \mathrm{LEF}_0}{\mathrm{LEF}_0} \times 100 \tag{7}$$

where $\mathrm{LEF}_{\mathrm{OV}}$, LEF_0 are load equivalency factors at any percent of overloaded vehicles OV and at 0% of overloaded vehicles, respectively.

To calculate the decrease of fatigue life (DFL) of a pavement structure due to overloaded vehicles, it was assumed that the fatigue life of this structure is equal to N_{100} standard 100 kN axle load and this pavement can carry in one case $N_{\mathrm{T},0}$ trucks with 0% of overloaded vehicles and in the second case $N_{\mathrm{T,OV}}$ trucks with OV percent of overloaded

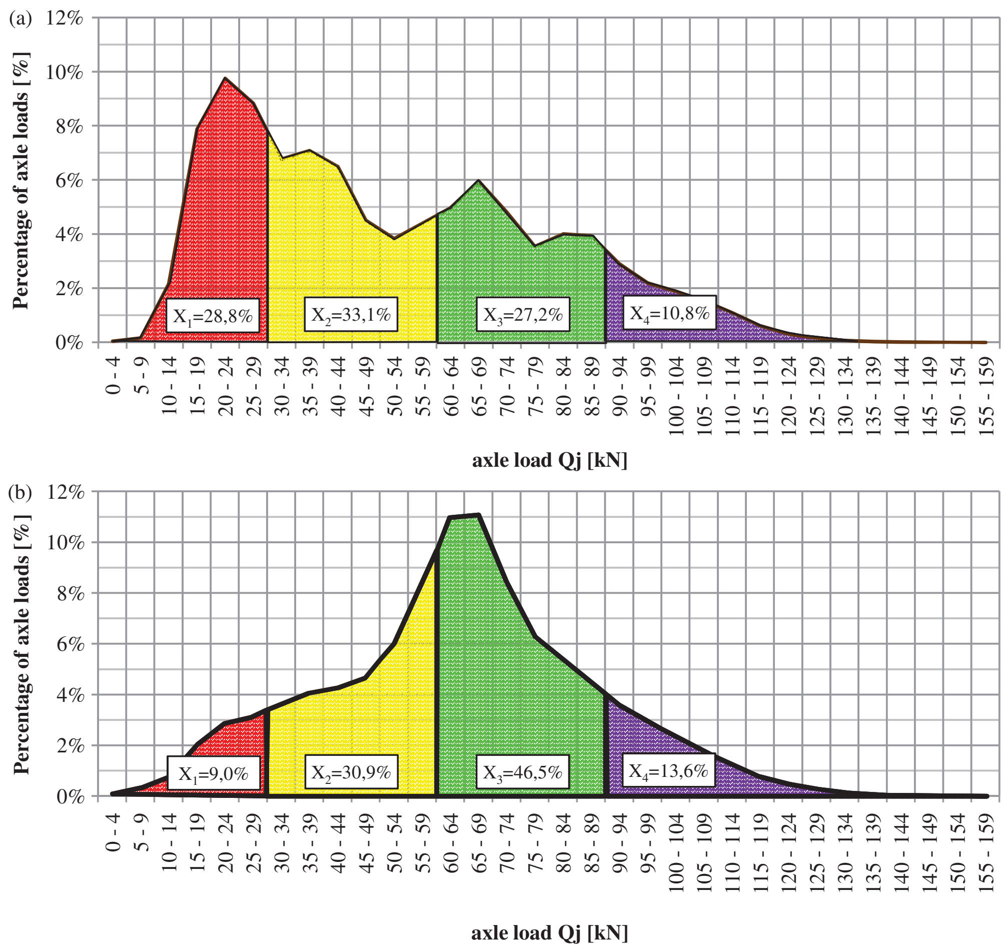

Figure 5. Example of values X_1, X_2, X_3 and X_4 from Equation (6) for (a) bimodal axle load distribution of DK79 and (b) unimodal axle load distribution of A2.

vehicles till fatigue damage, which is defined in this case as cracked area percent for the whole lane area. The load equivalency factors are equal respectively LEF_0 and $\mathrm{LEF}_{\mathrm{OV}}$. The following equation is valid:

$$N_{100} = N_{\mathrm{T},0} \times \mathrm{LEF}_0 = N_{\mathrm{T,OV}} \times \mathrm{LEF}_{\mathrm{OV}} \qquad (8)$$

The relative DFL due to OV percent of overloaded vehicles is equal to:

$$\mathrm{DFL}(\%) = \frac{N_{\mathrm{T},0} - N_{\mathrm{T,OV}}}{N_{\mathrm{T},0}} \times 100 \qquad (9)$$

Table 2. Characteristics of representative single-axle load distributions X_1, X_2, X_3, X_4 and percentage of overloaded vehicles OV.

Road designation	Percentage of representative single axles of load Qj: $Q_j < 30$ kN X_1 (%)	$30\,\mathrm{kN} \le Q_j < 60\,\mathrm{kN}$ X_2 (%)	$60\,\mathrm{kN} \le Q_j < 90\,\mathrm{kN}$ X_3 (%)	$Q_j \ge 90$ kN X_4 (%)	Percentage of overloaded vehicles OV (%)
A2	9.0	30.9	46.5	13.6	16.2
DK4	18.8	36.7	32.6	11.9	14.4
DK7	24.5	30.4	30.8	14.4	16.6
DK11	14.6	42.4	34.1	9.0	6.2
DK46	15.7	33.6	38.6	12.0	14.9
DK75	22.2	35.7	29.8	12.3	13.1
DK79	28.8	33.1	27.2	10.8	14.8
DK94	20.2	38.0	31.4	10.4	8.7

Table 3. Regression model coefficients.

a_1	a_2	a_3	a_4	R^2	Standard error of regression model	*LEF* relative standard error
0.09	0.07	0.37	0.74	0.996	0.023	8.8%

thus:

$$\text{DFL}(\%) = \left(1 - \frac{\text{LEF}_0}{\text{LEF}_{\text{OV}}}\right) \times 100 \qquad (10)$$

where, DFL is decrease of fatigue life caused by overloaded vehicles, $N_{\text{T},0}$ is number of trucks with 0% of overloaded vehicles till fatigue damage of the pavement, $N_{\text{T,OV}}$ is number trucks with OV percent of overloaded vehicles till fatigue damage of the pavement, LEF_0 is load equivalency factor at 0% of overloaded vehicles and LEF_{OV} is load equivalency factors at any percent of overloaded vehicles OV. The relationship between DFL and percentage of overloaded vehicles OV is shown in Figure 7(b).

Figure 7 shows data for the maximum, average and minimum values of *relative increase of* LEF and DFL from all eight WIM stations. In average, the LEF increases about 90% if percentage of overloaded vehicles increases from 0% to 20% (Figure 7(a)). The maximum relative increase of about 100% was noted for the DK79 road, from LEF = 0.15 to LEF = 0.3. It means that one pass of an average single truck axle on road DK79 is equivalent in its damaging effect to 0.15 passes of the standard axle load 100 kN if percentage of overloaded vehicle OV = 0%, and it increases up to 0.3 passes of the standard 100 kN axle load when percentage of overloaded vehicles increases up to 20%. Figure 7(b) for the DK79 road shows that the decrease in fatigue life of a pavement structure will be equal to 50% if percentage of overloaded vehicles increases from 0% to 20%. Figure 7(b) can be used to evaluate the detrimental effect of overloaded vehicles if their percentage is known.

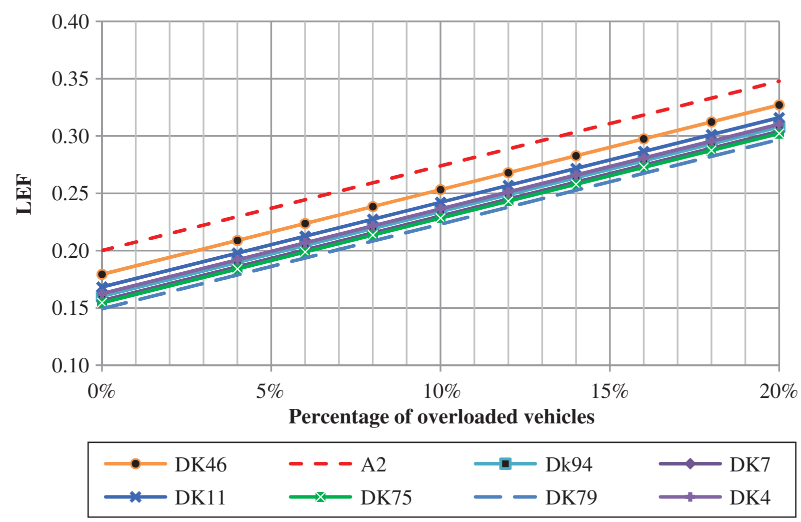

Figure 6. Relationship between LEF and the percentage of overloaded vehicles OV for all considered WIM stations.

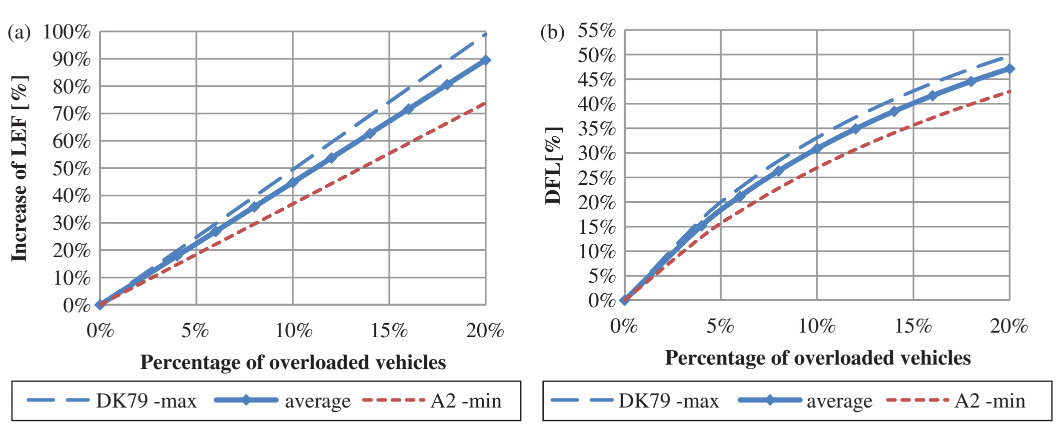

Figure 7. (a) *Relative increase of* LEF and (b) DFL in relation to percentage of overloaded vehicles OV.

However, the exact damaging effect of overloaded vehicles is dependent upon the axle load distribution, and somehow on the type and parameters of a pavement structure.

Example of calculation of the effect of overloaded vehicles on fatigue cracking life of asphalt layers

The example is to calculate the fatigue cracking life of asphalt layers of a given pavement structure in relation to a varied number of overloaded vehicles. The traffic loading characteristics were taken from a WIM station located on road DK79 (Table 1). The fatigue criteria for asphalt layers cracking were adopted from the *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavements Structures* (NCHRP 2004) for the bottom-up mode of cracking. The following input data were assumed in the example:

Pavement structure:

- The assumed pavement structure is presented in Figure 8. Thicknesses of layers was assumed for the sample structure from Polish *Catalogue of Typical Flexible and Semi-rigid Pavement Structures* (GDDKiA 2013). The moduli of elasticity E and Poisson's coefficients ν of pavement layers represent design annual values used in Poland for equivalent temperature $T = 13°C$ and loading time $t = 0.02$ s. The subgrade was improved to reach modulus of elasticity of $E = 100$ MPa.
- The bottom asphalt layer contains $V_b = 10\%$ of asphalt binder by volume and $V_a = 7\%$ of air voids.

Calculation of fatigue life of assumed asphalt pavement at 20% of cracked traffic lane area

Fatigue cracking life of asphalt layers was calculated from the formulas given in the *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavements Structures* (NCHRP 2004). First, the fatigue life was calculated and expressed in 100 kN standard axle loads. Next, the fatigue life was expressed in number of trucks passes that causes 20% of fatigue cracked area. The following are the results of calculations:

- $\varepsilon_t = 112.6 \times 10^{-6}$ is the tensile strain at the bottom of asphalt layers under 50 kN wheel load and contact pressure $q = 850$ kPa, calculated with BISAR 3.0 program (Shell 1998).
- $N_{f,50\%} = 17.43 \times 10^6$ of 100 kN standard axle loads repetitions to cause fatigue cracking occurring on FC = 50% of the traffic lane area.
- $D = 0.285$ – fatigue damage related to 20% of cracked traffic lane area.
- $N_{f,20\%} = D \cdot N_{f,50\%} = 4.97 \times 10^6$ of 100 kN standard axle loads repetitions to cause fatigue cracking occurring on FC = 20% of the traffic lane area.

The pavement structure can carry $N_{f,20\%}$ of 100 kN standard axle loads to occur 20% of cracked traffic lane area but the total number of representative single-axle loads, and also total number of trucks, depend on the LEF, which is a function of the percentage of overloaded vehicles and the character of representative single-axle load distribution which is specified by parameters X_1, X_2, X_3 and X_4.

Traffic load:

- The standard single axle of load $Q = 100$ kN with single wheel load of 50 kN and contact pressure $q = 850$ kPa was assumed for pavement analysis.
- The axle load distribution characteristic X_1, X_2 and X_3 to calculate LEF was taken from road DK79, as shown in Figure 8(a) and in Table 2.
- The percentage of overloaded vehicles OV was assumed in a range from 0% to 20% in 2% steps.
- The initial annual truck traffic after the road opening was assumed as equal to the present traffic measured on road DK79 and equal to 2.6×10^5 trucks/year.
- Average number of representative single axles per one truck was taken from the measurements on road DK79 and was equal to $f_a = 2.93$ axles/truck.
- Annual traffic growth was assumed as $p = 4\%$.

Number of trucks to cause 20% of fatigue cracked area

In pavement design and traffic analysis it is more common to use the number of trucks than the number of axles of vehicles and thus the number of representative single axles N was transformed into number of trucks, NT, by multiplying it by the factor f_a – average number of representative single axles per one vehicle. The number of

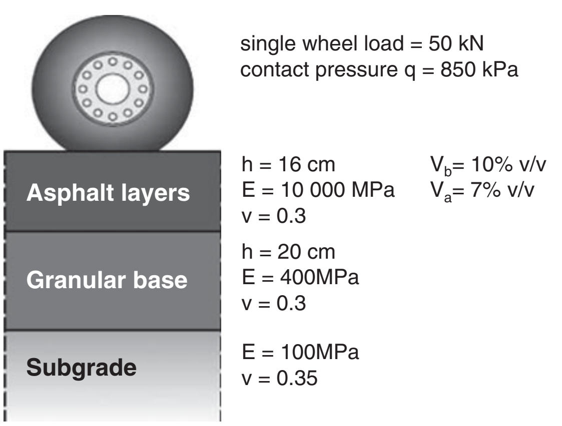

Figure 8. Model of assumed pavement structure.

trucks passes which are required to cause 20% of fatigue cracked area was calculated as a function of percentage of overloaded vehicles assuming truck traffic characteristics as for road DK79 from the following formula:

$$\mathrm{NT}_{f,20\%}(\mathrm{OV}) = \frac{N_{f,20\%}}{\mathrm{LEF(OV)} \times f_a} \tag{11}$$

where $\mathrm{NT}_{f,20\%}$ (OV) is number of trucks that passes to cause 20% of fatigue cracked area as a function of percentage of overloaded vehicles OV, $N_{f,20\%}$ is number of 100 kN standard axle loads to cause 20% of fatigue cracked area, LEF(OV) is load equivalency factor calculated from regression Equation (5) for road DK79, as a function of percentage of overloaded vehicles OV, from $\mathrm{OV} = 0$ to $\mathrm{OV} = 20\%$, f_a – average number of representative single axles per one truck taken from measurements on road DK79 and equal to $f_a = 2.93$ representative axles/truck. The calculated number of passes $NT_{f,20\%}$ is shown in Figure 9(a) in relation to percentage of overloaded vehicles OV.

Service life of pavement till occurrence of 20% of fatigue cracking in relation to percentage of overloaded vehicles

The initial annual truck traffic was assumed 2.6×10^5 trucks/year, as on road DK79, and annual growth of truck traffic is $p = 4\%$ the service life till occurrence of 20% of fatigue cracking was calculated for each percentage of overloaded vehicles and shown in Figure 9(b). As Figure 9 shows the increase of number of overloaded vehicles from 0% to 20% can reduce the fatigue life of assumed asphalt pavement twice. The decrease of overloaded vehicles from 20% to 10% increases the fatigue life of the pavement in question by about 4 years. The further decrease from 10% to 0% increases the fatigue life by about 6 years.

Conclusions

(1) Data from WIM stations on seven state roads and one motorway in Poland indicated that the percentage of overloaded vehicles was in the range from 6% to 16.5%. The lowest percentage was on a road where continuous control of traffic was performed. Most of overloaded vehicles exceeded the axle load limit, while the gross weight was exceeded less frequently.

(2) The axle load distribution of trucks and proportions between heavier and lighter axles varied for various WIM stations. The distributions were most often bimodal with two local extremes and in some case unimodal with only one extreme.

(3) It was found that the LEF which characterizes the aggressiveness of an average axle in a given flow of trucks to pavements structure is very well correlated with percentage of overloaded vehicles and characteristics of axle load distribution. The increase of LEF varied for the WIM stations in a range from 75% to 100% when percentage of overloaded vehicles increases from 0% to 20%.

(4) The overloaded vehicles affect significantly the fatigue life of pavement structures. The analysis has shown that the increase of percentage of overloaded vehicles from 0% to 20% can reduce the fatigue life of asphalt pavement in a range of 50%.

(5) The calculations of fatigue life of an asphalt pavement structure used in Poland considering data from traffic measurement at WIM stations indicated that the decrease of percentage of overloaded vehicles by 10% may cause the increase of service life of the pavement from 4 to 6 years.

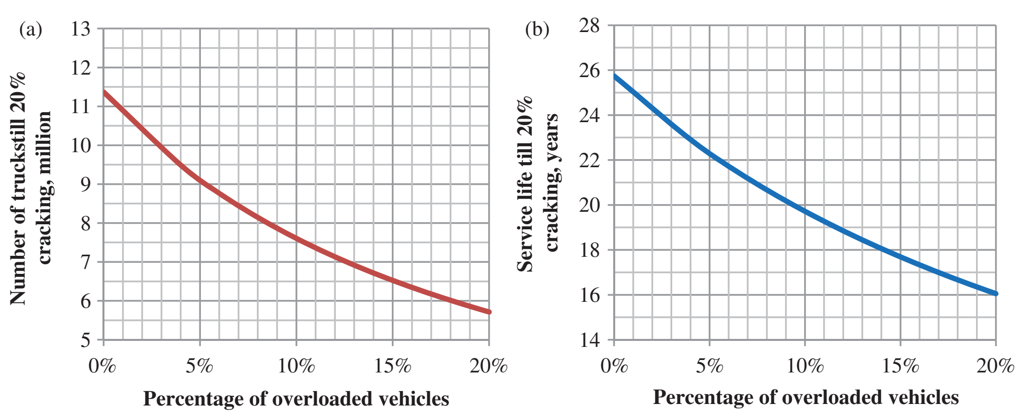

Figure 9. Fatigue life of pavement structure till occurrence of 20% of cracked area (a) number of trucks causing fatigue cracking and (b) service life till fatigue cracking.

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