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Determination of vehicles load equivalency factors for polish catalogue of typical flexible and semi-rigid pavement structures

Dawid Rys [a,]*, Jozef Judycki [a], Piotr Jaskula [a]

[a]*Gdansk University of Technology, Civil and Environmental Engineering, Narutowicza Street 11, Gdansk, PL 80-952 Poland*

Abstract

The new Polish Catalog of Typical Flexible and Semi-rigid Pavement Structures was introduced to use in practice in 2014. Much of works were focused on actualization of vehicles load equivalency factors. For this purpose data delivered from weigh-in-motion were analyzed. Four methods of determination of load equivalency factors for pavement structure design were compared. The analysis showed that fourth power equation, AASHTO 1993 and French LCPC methods derived load equivalency factors at similar level and these obtained factors can be underestimated in comparison to results delivered from mechanistic-empirical method. The paper presents a new approach to determine load equivalency factors with consideration of several issues which have a significant impact on traffic load assessment for pavement design. The weigh-in-motion data are available only for a small part of whole road network, thus to determine values valid for roads in whole country, the statistical analysis of load equivalency factor were performed. The dynamic coefficient can have significant impact on load equivalency factor, especially on minor roads with weak roughness of pavement surface. The weigh-in-motion derives archival data and it is known from long-term observations that vehicles weights and axle loads increase while pavement life period. Legal axle load limit and the percentage of overloaded vehicles have significantly impact on load equivalency factors. The final values of vehicle load equivalency factor were adjusted to include the coefficient of vehicle dynamic loads, growth of vehicle weights in the future and impact of overloaded vehicles.

Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)

Keywords: Equivalen axle load facto;, pavement design; load equivalency factor; weigh-in-motion; overloaded vehicles; asphalt pavements

* Corresponding author. Tel.: +4858 347 27 82; fax: +4858 347 10 97.
E-mail address: dawrys@pg.gda.pl

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1. Introduction

1.1. Background

The Polish Catalogue of Typical Flexible and Semi-rigid Pavement Structures (GDDKiA, 2014) is a legal document used to design pavement structures and determining the basic technological requirements. The previous catalogue was introduced to use in 1997. Since that time the traffic have grown rapidly and also the vehicle class distribution has changed significantly. After the Polish accession to the European Union after 2004 the new legislation and European Council Directive 96/53/WE came into force in Poland. Consequently the gross weights limits and maximum axle loads limits of vehicles have increased. Moreover significant part of vehicles exceed the maximum legal limits causing faster pavement failure. In the recent years the system of weigh-in-motion have been intensively developed, what improved the control of overloaded vehicles and also provided the data of vehicle axle loads and traffic characteristic. It contributed to the need for determination of new vehicles load equivalency factors for Polish Catalogue of Typical Flexible and Semi-rigid Pavement Structures. The new Catalogue was developed in the Gdansk University of Technology, evaluated by Polish specialist and then introduced as legal document by General Directorate for National Roads and Motorways in 2014.

1.2. Objectives and scope

The paper presents a part of wider research conducted to actualize the Polish Catalogue of Typical Flexible and Semi-rigid Pavement Structures (Judycki et al. 2014). The main objective of the paper is to present the new approach of determination of vehicle load equivalency factor with usage of the data from weigh-in-motion. The paper presents the results of comparison of the following methods: fourth power law, AASHTO 1993, French LCPC 1998 and mechanistic-empirical approach. The final values of vehicle load equivalency factors were adjusted to include the coefficient of vehicle dynamic loads, growth of vehicle weights in the future and the impact of maximum legal axle load limit and overloaded vehicles. Due to limited space in this article only the final results and examples of analyzes were presented. More detailed description of the analysis was presented by Judycki et al. (2014).

2. Procedure of analysis

The procedure of analysis and determination of load equivalency factors is presented in the figure 1. Load equivalency factor (abbreviated further as LEF) express the ratio of vehicle number to the number of 100 kN equivalent standard axle. In the analysis load equivalency factors were calculated for each vehicle separately. Equivalent standard axle loads F_j were calculated for each of axles in particular vehicles and further they were summarized to express load equivalency factor for each vehicle F_v. Then analysis of vehicle load equivalency factors were conducted in accordance to the procedure presented in the figure 1. Other factor that affect on load equivalency factors were included in the calculations by introducing corrective factors K. The analysis were performed individually for three vehicles category:

- single commercial vehicles (abbreviated further as C),
- commercial vehicles with trailer or semitrailer (abbreviated further as C+P)
- public service vehicles (abbreviated further as A).

Road importance, technical class and category can also have an influence on traffic of heavy vehicles and consequently on values of LEF, thus in the analysis three roads groups were considered:

- motorways and expressways,
- national roads,
- other roads (including province, regional and local roads).

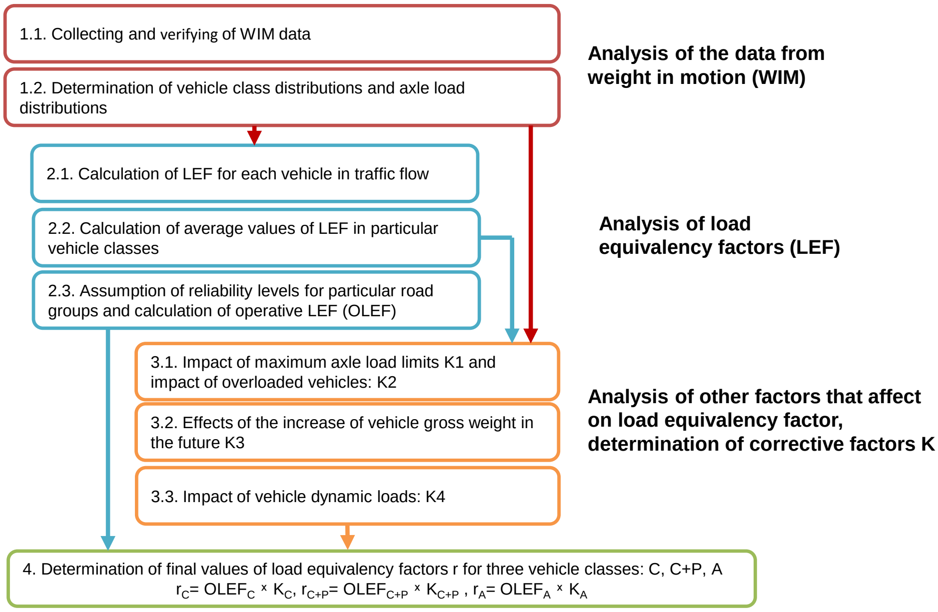

Fig. 1. Procedure of determination of load equivalency factors.

3. Measurement of heavy traffic

Data used in analysis of heavy traffic loads were delivered from five weigh-in-motion (WIM) stations loacated on Polish national roads and motorway. The WIM stations are equipped in the bending plate sensors PAT DAW 100® (A2 and DK11) or in the piezo-electric quartz sensors Kistler Lineas® (DK 46, DK 4, DK 1). The systems of automatic vehicle classification are also installed in all of the stations. The WIM stations can be classified as a class B+(7) according to COST 323 WIM classification (Jacob, 1999). The information about WIM data and measurement period are given in the table 1. The data considered in this study were collected from 2009 to 2012 but the period of measurement can differ for particular WIM stations (see table 1).

The raw WIM data were verified using series of filters of vehicles parameters (e.g. axle loads, total length, axle configurations etc.). The filters were set in accordance with the WIM Data Analyst Manual (FHWA, 2010) and NCHRP report 538 (NCHRP, 2005) and vehicle technical parameters review. Similar verification process was proposed by Zofka et. al (2014). The filtering process was focused on identifying and removing invalid records from the database and choosing to further analysis only these vehicles, which gross weigh exceeded 3 500 kg. To sum up more than 15 million of all types of vehicles were recorded, including cars, vans etc., out of that more than 4,2 million records of heavy vehicles were used in the analysis.

Table 1. Measurement period and number of vehicles records used in analysis.

WIM station (road no./location)	Traffic directions	Total number of record of heavy vehicles	Measurement period
DK 46 Grodziec	N, S	635 529	Dec. 2010 – Feb. 2012
A2 Emilia	E, W	1 418 112	Jan. 2011 – Feb. 2012
DK 11 Byczyna	S	655 225	Sep. 2009 – Feb. 2012
DK 4 Wola Debinska	E, W	1 380 506	Jul. 2010 – Feb. 2012
DK 1 Wloclawek	S	143 579	Jan. 2011 – Aug. 2011

4. Analysis of load equivalency factors

4.1. Comparison of calculation methods

In the analysis four methods of calculation of LEF were considered:

1. Power equation model - fourth power equation for flexible pavement and equation with exponent 12 for semi-rigid pavements.
2. AASHTO method (1993) – calculations were carried out in two alternatives: for medium-loaded (KR3) and for heavy-loaded (KR6) flexible pavement structures. Thickness and materials characteristic were assumed in accordance to the Polish catalog from 1997 (GDDP, 1997).
3. LCPC method (French Institute of Science and Technology for Transport, LCPC, 1998) – calculations were conducted for flexible and semi-rigid pavements
4. GUT method (Gdansk University of Technology), (Judycki et al., 2006, Judycki, 2010, 2011) – calculations were conducted for flexible and semi-rigid pavements in two alternatives: for medium-traffic (KR3) and for heavy-traffic (KR6). Three criteria of pavement fatigue were considered: fatigue cracking of asphalt layers, fatigue cracking of cement treated base, subgrade deformation.

Each of the method included the impact of multiple axles (tandem and tridem). The example of average LEF for flexible pavements obtained for road DK46 is presented in the figure 2a. It can be concluded that average values of LEF are similar for fourth-power equation, AASHTO 1993 method and LCCP method. In the case of GUT method the mean value of LEF depends on the fatigue criteria. For analyzed pavement structures LEF are higher for criteria of asphalt fatigue cracking than for criteria of subgrade deformation. It can be also concluded that mean values of LEF are higher for thinner pavements structures (KR3) for each of calculation method.

Differences in results obtained for calculation for flexible and semi-rigid pavements are presented in the figure 2b. Method of calculations has a significant influence on mean values of LEF. Results obtained for power equation model with exponent of 12 are higher by about 1,5 times than results obtained from four power equation. GUT method for criteria of fatigue cracking of cement treated base gave results lower than for criteria of fatigue cracking of asphalt layers and subgrade deformation. It is worth to note that additional analysis of load equivalency factors calculated from GUT method for semi-rigid pavements revealed that cement treated base can have much higher fatigue life in comparisons to asphalt base provided that the overloaded vehicles do not occur. AASHTO method cannot be applied for semi-rigid pavements. Results obtained for LCPC method are significantly higher than for GUT method and power equation model. The LCPC method was developed for standard axle load 130 kN with dual tire, which is different than standard axle assumed in Poland. There are set higher maximum axle loads limits in France (130 kN) than in Poland (100 kN or 115 kN) thus the real axle loads are also higher in France. These factors have a significant influence on calculations results due to power exponent assumed for semi-rigid pavements which is equal to 12, and also due to effects of multiple axles. It can be concluded that LCPC method for semi-rigid pavements in Polish traffic conditions is not valid. Finally there were not specified LEF for design of semi-rigid pavements but the effect of traffic load impact on cement treated base layer was included in the mechanistic-empirical calculations of fatigue life (Judycki et al., 2014). Fatigue life of cement treated base layer in the precracked stage, expressed by the number of equivalent 100 kN standard axle loads, was reduced by a factor 1,5, which corresponds to the increased impact of heavy traffic on semi-rigid pavements.

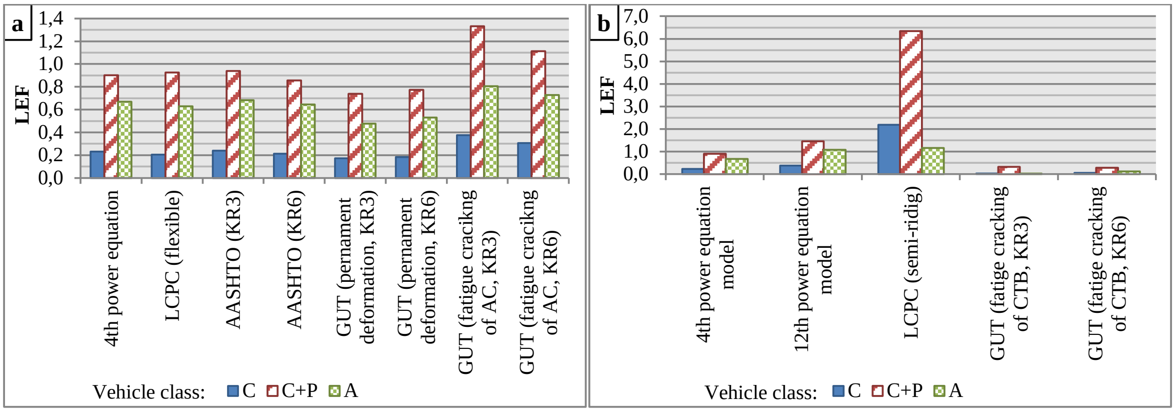

Fig. 2. Comparison of load equivalency factors LEF, calculated for example road DK46 for a) flexible pavements, b) semi-rigid pavements.

4.2. Determination of average and operative values of load equivalency factors

Average values of LEF for each WIM stations are given in table 2 and it can be concluded, that these values differs for particular stations. It means that LEF depends on the local traffic conditions on a specific road section. For this analysis there were available WIM data from only five road sections and for other road sections mean values of LEF would be different. For this reason an operative load equivalency factors (abbreviated as OLEF) were introduced into analysis. OLEF express the percentile of LEF for probability α, and it was calculated from the following formula:

$$OLEF = LEF + t_{\alpha}\sigma_{LEF} \quad (1)$$

where:
OLEF – operative load equivalency factor,
LEF – average load equivalency factor,
σ_{LEF} – standard deviation of LEF,
t_{α} – percentile of normal distribution for probability α.

The results of calculation of OLEF are presented in the table 3. Values of OLEF were calculated using three probability levels α, depending on the road group:

- Motorways and expressways α=95%,
- National roads α=80%,
- Other roads (province, local) α=60%.

Table 2. Average load equivalency factors (LEF) and standard deviations of LEF for flexible pavements.

Calculation method	Vehicle category	WIM station DK46	A2	DK11	DK4	DK1	Average LEF	Standard deviation σLEF
Fourth power equation	C	0.237	0.236	0.266	0.229	0.278	0.249	0.019
	C+P	0.928	1.028	0.631	0.871	0.860	0.864	0.131
	A	0.698	0.803	0.786	0.878	0.794	0.792	0.057
AASHTO	C	0.247	0.245	0.278	0.236	0.291	0.260	0.021
	C+P	0.964	1.060	0.663	0.906	0.894	0.898	0.131
	A	0.713	0.805	0.798	0.887	0.804	0.802	0.055
LCCP	C	0.211	0.217	0.227	0.209	0.242	0.221	0.012
	C+P	0.955	1.077	0.567	0.893	0.868	0.872	0.169
	A	0.659	0.829	0.763	0.878	0.779	0.782	0.073
GUT	C	0.320	0.301	0.352	0.287	0.376	0.356	0.054
	C+P	1.099	1.158	0.851	1.039	1.042	1.003	0.097
	A	0.679	0.711	0.737	0.799	0.737	0.796	0.136

Table 3. Operative load equivalency factors for three probability levels α.

Calculation method	Vehicle category	Road type and probability level α Motorways and expressways α = 95%	National roads α = 80%	Other roads α = 60%
Fourth power equation	C	0.303	0.279	0.267
	C+P	1.226	1.064	0.986
	A	0.951	0.879	0.846
AASHTO	C	0.319	0.292	0.280
	C+P	1.261	1.098	1.021
	A	0.955	0.886	0.854
LCCP	C	0.397	0.377	0.358
	C+P	1.258	1.196	1.135
	A	0.817	0.793	0.770
GUT	C	0.255	0.240	0.233
	C+P	1.340	1.130	1.031
	A	0.985	0.894	0.851
Average	C	0.318	0.297	0.284
	C+P	1.271	1.122	1.043
	A	0.927	0.863	0.830

5. Parameters affecting load equivalency factors

5.1. Maximum legal axle loads and overloaded vehicles

Polish law provides three levels of maximum legal axle load limits. The limits for single drive axle are equal to 115 kN for highways, motorways and majority of national roads, 100 kN for national and provincial roads and 80 kN for other roads. In the future whole road network will be adjusted to carry vehicles with maximum legal axle loads 115 kN.

It was revealed that maximum legal axle load limit has an influence on axle load distribution and consequently on the values of LEF (Rys et al., 2015). LEF values are lower for roads where lower axle loads limits are permitted. Thus for determination of final values of LEF for group of other roads, where maximum legal axle load for pavement design were assumed as 100 kN, a decreasing corrective factor K1 was introduced. The values of K1 were determined on the base of comparison of LEF values, calculated for roads with maximum axle load 100 kN (DK46, DK11) and with maximum axle load limit 115 kN (A2, DK1, DK4). Following conclusions can be stated:

- There is no difference in LEF for vehicle class C.
- LEF values are 5% lower in average for vehicle class C+P.
- LEF values are 10% lower in average for vehicle class A.

A part of vehicles exceed the legal limits of gross weight or axle loads and they are called overloaded vehicles. Overloaded vehicles occur less frequently in comparison to properly loaded vehicles, but due to their greater potential to cause damage they significantly contribute to the distress of pavement structure. The annual average percentage of overloaded vehicles varies from 6% to 25% what makes it a serious problem in Poland (Rys, 2012). The phenomenon intensifies when the control of traffic is poor. Weigh-in-motion is a part of systems of vehicle overloading control thus the percentage of overloaded vehicles can be higher on roads where WIM systems are not installed. In other words, drivers who are aware of overloading their vehicles can chose an alternative trip route to avoid the control on WIM station.

It was revealed that increase of load equivalency factors is proportional to the increase of percentage of overloaded vehicles (Rys et al., 2015). Figure 2 presents an example of relationship between average daily load equivalency factor calculated from fourth power equation and daily percentage of overloaded vehicles. For each of WIM stations and each of vehicle class the linear regression models between percentage of overloaded vehicles and load equivalency factors were determined. In the next stage these models were used to calculate correction coefficient K2 according to the formula (2). To calculate K2 it was assumed the percentage of overloaded vehicles as for motorway A2, because it was found in the interview that the control is the least frequent on this station.

$$K2 = \sum_{i=1}^{5} \frac{a_i \cdot u_{A2} + b_i}{LEF_i} \tag{2}$$

where:
K2 – correction coefficient including the impact of overloaded vehicles,
a_i, b_i – coefficient derived from linear regression models (Fig 2.),
u_{A2} – average annual percentage of overloaded vehicles on WIM station A2,
LEF_i – average annual load equivalency factor on a given WIM station i.

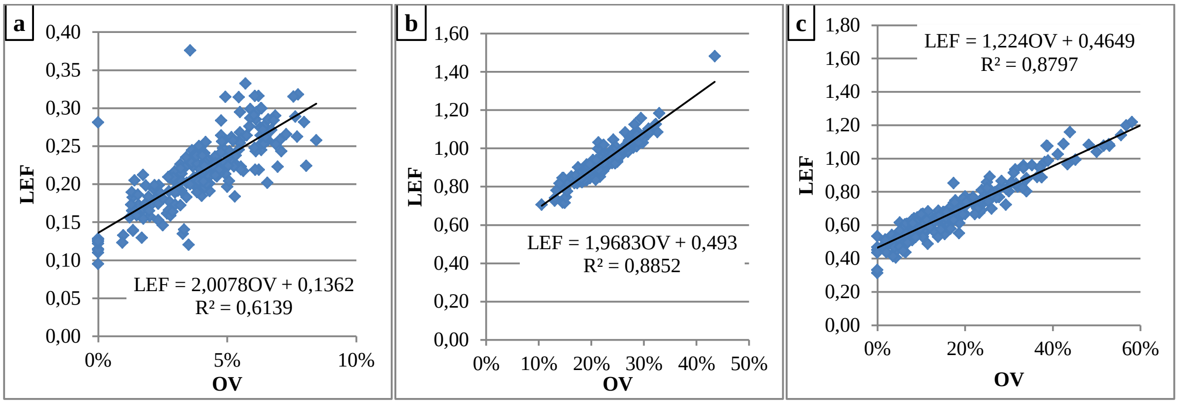

Fig. 2. Example of relationship between average daily load equivalency factor LEF and daily percentage of overloaded vehicles for WIM station DK46 for vehicle classes: (a) single commercial vehicles units, (b) commercial vehicles with trailer or semitrailer and (c) public service vehicles.

5.2. Growth of vehicle weights in the future

Observations carried out in United Kingdom (Atkinson, 2004) and changes in load equivalency factor in German Catalog of Typical Pavement Structures RSTO 01 and RSTO 12 (FGSV 2001, 2012) showed that vehicle loads increase in long period time. It is a consequence of cost optimization of transport which is based on the increase of vehicles capacities. In other word the number of empty vehicles or half-loaded vehicles will decrease and number of fully loaded vehicles will increase, what will cause the increase of axle loads, and as a consequence, the increase of load equivalency factor. New flexible and semi-rigid pavement structures are design for time period from 20 to 30 years and during this time vehicles loads will increase with a high probability. This phenomenon was included in the analysis by use of correction coefficient K3. The procedure of estimation of correction factor K3 was following:

a) Determination of empirical distributions of gross weight for particular vehicle classes and for particular WIM stations.
b) Calculations of average values of load equivalency factors (from four power equation) for each of gross mass intervals.
c) Determination of the forecast of empirical distribution of vehicle gross weight, separately for motorways, expressways and other roads.
d) Calculation of average load equivalency factors for actual and forecasted distribution of vehicle gross weights.
e) Determination of correction factor K3 as an average ratio of actual LEF to the LEF determined from the forecast of gross weight distributions.

Figure 3 presents an example of the forecast of empirical distribution of vehicle gross weight. It was assumed that a certain percentage of vehicles number will shift from a group of lighter vehicles into a group of heavier vehicles.

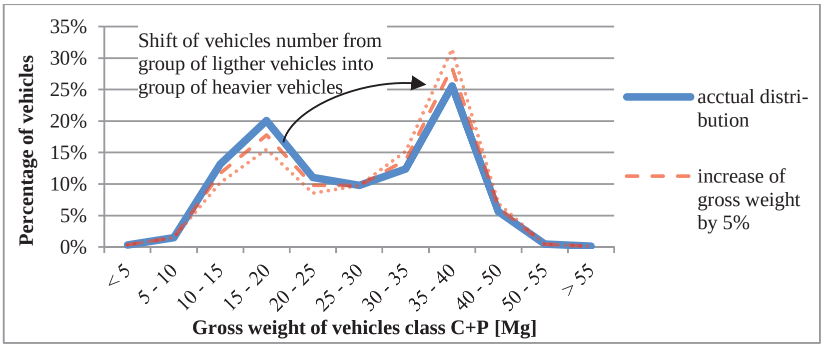

Fig. 3. Example of the forecast of increase of gross weight for articulated commercial vehicles with trailer or semi-trailer (C+P), road DK4.

5.3. Vehicle dynamic loads

However WIM include measurements of dynamic axle loads, the results provided from load sensors are transformed by calibration factors to represent static loads of axles. Therefore calculations carried out for data of static loads do not include the dynamic coefficient of axle loads. In order to estimate an influence of vehicles dynamic loads on load equivalency factors the correction coefficient K4 was determined according to the formula:

$$K4 = \frac{\sum_{i=1}^{n}(1+\mu_i \cdot DLC)^4}{n} \quad (3)$$

where:
K4 – correction coefficient to include the impact of vehicles dynamic loads,
μ_i – percentile of normal distribution for a given probability level α (α=98% was assumed) ,
DLC – dynamic load coefficient, ratio of static load to the standard deviation of dynamic loads,
n – number of assumed intervals of dynamic axle loads within an assumed probability level α

The formula 3 was derived from Judycki et al (2014). The values of DLC were calculated on the basis of FHWA report (Misaghi, 2010) where mathematical models of dynamic loads of vehicles were developed. DLC is closely related with road roughness, expressed by IRI, vehicle speed and mechanic parameters of axle suspension. In order to calculate DLC values, average values of IRI were assumed on the basis of the report of technical condition of polish national roads (GDDKiA, 2012). Average vehicle speed was delivered from the measurements provided from the WIM stations. Suspension mechanic parameters were assumed in accordance with the FHWA report (Misaghi et al., 2010). Table 4 present the values of DLC and correction coefficient K4 calculated for three groups of roads: highways and motorways, national roads and other roads.

Table 4. Correction factor K4 and parameters assumed in order to calculate dynamic load coefficient DLC.

Parameter	Highways and motorways	National roads	Other roads
Road roughness IRI [mm/m]	1.5	2.5	3.0
Vehicle speed v [km/h]	90	70	70
Dynamic load coefficient DLC [-]	0.145	0.155	0.19
Probability level α	98%	98%	98%
Correction factor K4 [-]	1.19	1.22	1.33

6. Determination of final values of load equivalency factors

The safety reserve was include in the final values of load equivalency factors by introducing:

- reliability levels for particular road groups and determination of operative load equivalency factors,

- correction coefficient K which include effect of: maximum legal axle load limit (K1), vehicle overloading (K2), increase of gross weight of vehicles in the future (K3), vehicle dynamic loads (K4).

Values of corrective factors K1, K2, K3 and K4 for particular vehicle classes and roads groups are presented in table 5. Correction coefficients K were calculated from the formula (4) and they are presented in table 6.

$$K = K1 \cdot K2 \cdot K3 \cdot K4 \quad (4)$$

Table 5. Correction coefficients K1, K2, K3, K4 used to determine the final values of load equivalency factors.

Vehicle category	**K1** – factor including effect of maximum legal axle load limit		**K2** – factor including the effect of overloaded vehicles	**K3** – factor including the possibility of increase of gross weight in future		**K4** – factor including effect of vehicle dynamic loads		
	Max. legal axle load 115 kN	Max. legal axle load 100 kN	All roads	Motorways, expressways and national roads	Other roads	Motorways and expressways	National roads	Other roads
C	1.00	1.00	1.07	1.21	1.10	1.19	1.22	1.33
C+P	1.00	0.95	1.12	1.15	1.08	1.19	1.22	1.33
A	1.00	0.90	1.00	1.11	1.06	1.19	1.22	1.33

Table 6. Correction factors K used to determine the final values of load equivalency factors.

Vehicle category	Correction coefficient K			
	Motorways and expressways	National roads	Other roads	
	Maximum axle load limit assumed for pavement design			
	115 kN	115 kN	115 kN	100 kN
C	1.54	1.58	1.57	1.57
C+P	1.53	1.57	1.61	1.53
A	1.32	1.35	1.41	1.27

The final values of LEF for pavement design are the results of multiplying the operative load equivalency factors OLEF, given in table 3, by correction factors K, given in table 6. Results rounded to 0,05 of this multiplication are given in table 7. Table 7 presents the final values of LEF assumed for calculation of design traffic in the Polish Catalogue of Flexible and Semi-rigid Pavement Structures (2014).

Table 7. Final values of load equivalency factors for Polish Catalogue of Flexible and Semi-rigid Pavement Structures (2014).

Vehicle category	Examples of vehicles	Group of roads			
		Motorways and expressways	National roads	Other roads	
		Maximum legal axle load limit, assumed for pavement design			
		115 kN	115 kN	115 kN	100 kN
Single commercial vehicles **C**		0.50	0.50	0.45	0.45
Commercial vehicles with trailer or semitrailer **C+P**		1.95	1.80	1.70	1.60
Public service vehicles **A**		1.25	1.20	1.15	1.05

7. Summary

- Up to 5 million heavy vehicles were analyzed with the usage of the data from weigh-in-motion on four national roads and one motorway in order to determine new load equivalency factors for Polish Catalogue of Typical Flexible And Semi-Rigid Pavement Structures.
- Four calculation methods: fourth power equation, AASHTO 1993 (USA), LCPC (France), Gdansk University of Technology GUT (Poland), were compared and used to determine load equivalency factors. In mechanistic-

empirical approach (GUT) higher values of load equivalency factors were found out for criteria of asphalt layers cracking than for permanent subgrade deformation.
- The detrimental effect of traffic loads is higher for thinner pavements structures.
- LCPC method for semi-rigid pavements is not valid for Polish traffic conditions. Load equivalency factors calculated from GUT method for semi-rigid pavements indicated that cement treated base can have higher fatigue life in comparison to asphalt base provided that overloaded vehicles do not occur.
- The increase of maximum legal axle load causes increase of average load equivalency factors. It was found that the load equivalency factor are very well correlated with percentage of overloaded vehicles.
- It can be concluded from the observation carried out in well developed countries like Germany and United Kingdom that vehicles gross weights will increase in the future, which will cause increase of load equivalency factors.
- Dynamic loads of vehicles have detrimental effect on pavement structure and they depend on pavement roughness, vehicle speed and suspension parameters. Dynamic loads affect significantly on the values of load equivalency factors.
- The safety reserve was included in the final values of load equivalency factors by introducing: reliability levels depending on the category of the road and corrective factors K including effect of: maximum legal axle load limit vehicle overloading, possibility of increase of gross weight of vehicles in the future and vehicle dynamic loads.

References

AASHTO (American Association of State Highway and Transportation Officials), 1993. The AASHTO Guide for Design of Pavement Structures. Washington.

Atkinson V. M., Merrill D., Thom N., 2006. Pavement wear factors. Transportation Research Laboratory TRL, Published Project Report PPR 066, United Kingdom.

FGSV (German Road and Transport Congres), 2001. Richtlinien für die Standardisierung des Oberbaues von Verkehrsflachen RSTO 01, (Catalog of Typical Pavement Structures). Koln, Germany (in German).

FGSV (German Road and Transport Congres), 2012. Richtlinien für die Standardisierung des Oberbaues von Verkehrsflachen RSTO 12 (Catalog of Typical Pavement Structures). Koln, Germany (in German).

FHWA (Federal Highway Administration), 2010. Quinley R. WIM Data Analyst's Manual.

GDDKiA (General Directorate for National Roads and Motorways), 2012. Radzikowski M., Foryś G., Frączyk K. Report of technical condition of national road network in 2011. Warsaw, Poland. (in Polish)

GDDKiA (General Directorate for National Roads and Motorways), 2014. Judycki J., Jaskula P., Pszczola M., Alenowicz J., Dolzycki B., Jaczewski M., Rys D., Stienss M. Catalogue of typical flexible and semi-rigid pavement structures. Gdansk University of Technology, Gdansk, Poland.. (in Polish)

GDDP (General Directorate for Public Roads), 1997: Catalogue of typical flexible and semi-rigid pavement structures. Road and Bridge Research Institute, Warsaw. (in Polish)

Jacob B., 1999. COST 323 Weigh in motion of road vehicles. Final Report, appendix 1 European WIM Specification.

Judycki J. Grajewska A., Wróbel M. 2006: Develompent of recomendations for calculation of equivalen axle load factors for design of flexible and semi-ridig pavements structures. Final report. Gdansk University of Technology, Gdansk, Poland. (in Polish).

Judycki J., 2010. Determiantion of axle load equivalency factors on the basis of fatigue criteria for flexible and semi-rigid pavements. Journal of Road Materials and Pavement Design, vol. 11, nr 1/2010, s.187-202.

Judycki J., 2011. Equivalent axle load factors for design of rigid pavements derived from fatigue criteria , Baltic Journal of Road and Bridge Engineering, vol. 6, no. 4, 2011, s. 219-224

Judycki J. Jaskuła P, Przczola M., Jaczewski M., Ryś D., Alenowicz J., Dolzycki B., Stienss M, 2014. Analysis and design of flexible and semi-rigid pavement structures. WKL, Warsaw. (in Polish)

LCPC (French institute of science and technology for transport), 1998. Catalogue of new pavement structures, Pars, France. (in French)

Misaghi S., Nazarian S., Carrasco C. J. 2010: Impact of Truck Suspension and Road Roughness on Loads Exerted to Pavements, The University of Texas, FHWA, El Paso.

NCHRP (National Cooperative Highway Research Program) 2005. Traffic Data Collection, Analysis, and Forecasting for Mechanistic Pavement Design. Report 538.

Ryś D., Judycki J., Jaskuła P., 2015. Analysis of effect of overloaded vehicles on fatigue life of flexible pavements based on weigh in motion (WIM) data, International Journal of Pavement Engineering, doi: 10.1080/10298436.2015.1019493

Ryś D., Judycki J., Jaskuła P., 2015. Analysis of axle loads of heavy vehicles on the base of the data from weigh in motion (WIM). Drogownictwo 10/2015 (in Polish).

Zofka A., Urbaniak A., Maliszewski M., Bankowski W., Sybilski D., 2014. Site specific traffic inputs for mechanistic-empirical pavement design guide in Poland. Transportation Research Board, 93rd Annual Meeting, Washington., USA.