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Study on the accuracy of axle load spectra used for pavement design

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ABSTRACT
Weigh-in-Motion (WIM) systems are used in order to reduce the number of overloaded vehicles. Data collected from WIM provide characteristics of vehicle axle loads that are crucial for pavement design as well as for the development of pavement distress prediction models. The inaccuracy of WIM data lead to erroneous estimation of traffic loads and in consequence inaccurate prediction of pavement distress process. The objective of the paper is to present a new methodology of heavy traffic axle load spectra (ALS) correction due to weighing errors (systematic and random) that occur in WIM systems. The theoretical solution which is proposed in the paper was validated successfully. The method enables correction of erroneous data to make traffic load statistics used for pavement design more reliable and precise, with no necessity to remove high number of records, as it is used in other methods. The practical meaning of the newly developed method was emphasised by analysis of the effect of relative and random error of WIM data on pavement fatigue life estimation, as well as on the estimated percentage of overloaded vehicles. Mechanistic-empirical approach (M-EPDG) was used for this purpose.

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Introduction

Meaning of weigh-in-Motion data and its accuracy in pavement design

Weigh-in-Motion (WIM) systems have been known for decades, but in the last ten years they have been dynamically developed in order to improve the control over vehicle loads and to reduce the number of overloaded vehicles. Axle load sensors of such systems are embedded directly in the pavement of the road, perpendicularly to the direction of the traffic. Such construction of the WIM systems enables weighing of vehicles in motion without the need to stop them and makes the control effective, as each vehicle passing over the WIM site is weighed. The data from WIM systems are collected and, due to continuous measurement of traffic, they provide characteristics of vehicle axle loads that are crucial for pavement design.

For pavement design and performance analysis, discrete distributions of vehicle axle load are used, which represent percentage of axles falling into a set of axle load intervals. Such distributions are referred to as axle load spectra (further abbreviated as ALS). Besides the discrete description of ALS, some research works (Mohammadi and Shah 1993, Wu 1996, Timm et al. 2005, Wang et al. 2007, Haider et al. 2009, Macea et al. 2015) developed models that describe ALS by mathematical functions, but they have not yet been adopted for practical application. In pavement design ALS are further transformed into load equivalency factors or are used directly as input data. Load equivalency factors are part of older pavement design methods and are calculated according to the fourth power equation, AAHSTO 1993 equations, LCPC equations (LCPC 1998), or other methods, like those developed by Judycki (Judycki 2010, 2011). Examples of application of ALS in calculation of load equivalency factors were published in (Atkinson et al. 2005, Turochy et al. 2005, Rys et al. 2016a). According to the most advanced pavement design method M-EPDG (Mechanistic Empirical Pavement Design Guide) (NCHRP 2004), ALS are set as input data and are determined individually for single, tandem, tridem and quad axles, across separate vehicle classes and months (Atkinson et al. 2005). Some works include studies of implementing ALS in M-EPDG calculations (Turochy et al. 2005, Tran and Hall 2006, Haider and Harichandran 2007, Wang et al. 2007, Zofka et al. 2014). Regardless of the method, ALS have a significant impact on prediction of pavement performance. Therefore, high precision of ALS obtained from WIM data is important in terms of pavement performance analysis.

The greatest disadvantage of data collected from WIM systems is the fact that the accuracy of weighing results is sensitive to numerous factors. While system calibration minimises the weighing errors, it does not eliminate them. Typically, calibration of WIM systems is performed periodically, with the use of previously weighed vehicles. Even if WIM system accuracy is satisfactory after the calibration, it can deteriorate with time and cause collection of erroneous data (Mai et al. 2013, Farkhideh et al. 2014). There are several sources of the loss of accuracy, including: sensitivity of load sensors to changes in temperature (Gajda et al. 2013), fatigue of load sensors (Papagiannakis et al. 2007) and changes of stress distribution in the pavement structure resulting from variable temperature (Burnos and Rys 2017).

WIM data quality can be of great importance when they are used for pavement design. The effect of systematic error of axle

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loads on pavement design was investigated in the following works: (Prozzi and Hong 2007) and (Haider et al. 2012). Their authors noted that bias in axle load spectra can translate up to five-year errors estimated service period in the case of flexible pavements and up to ten years in the case of rigid pavements. It is noteworthy that while previous studies investigated the effect of systematic errors on pavement design, the problem of influence of random error still remains unrecognised. The random error in ALS arises from dynamic loads, changes in site conditions and equipment accuracy. It is very difficult to remove this type of error just by WIM calibration.

Currently developed methods of verification of WIM data for pavement design, including manuals (NCHRP 2005, Quinley 2010), are based on filtering and removing of invalid records. According to studies of Mai et al. (2013), 23.8% of records from WIM database may create an error in ALS and should be removed. Such a high amount of removed data may make it difficult or even impossible to identify periodic changes in traffic loads, including seasonal, weekly and daily changes in vehicle weight. Another problem is the proper estimation of the scale of vehicle overloading. There is still a lack of knowledge on how to correct the data that include errors in order to make traffic load statistics more reliable and precise.

Objective and scope

The objective of the paper is to present a new methodology of axle load spectra correction due to weighing errors (systematic and random) that occur in WIM systems. The scope of the paper is illustrated in Figure 1, which shows particular steps taken to develop and validate the new methodology of axle load spectra correction and also to emphasise the practical meaning of the new method. Figure 1 also includes the structure of the paper and names of particular sections.

Identification of errors in weigh-in-Motion systems

The accuracy of axle load measurement in WIM systems can be divided into two components: random and systematic error. Random error occurs mainly due to the nature of the measurement of variable axle loads of moving vehicles and heterogeneous sensitivity of the sensor along its length (Burnos et al. 2018). Systematic error is related to the sensor/pavement complex and depends on the:

- Sensor intrinsic error – related to the change in the electrical parameters of the sensor under the impact of temperature change.
- Pavement/sensor complex external error –a combination of the sensor intrinsic error and additional errors which occur after the sensor is installed in the pavement. The source of the additional errors is the pavement, as its properties depend on the temperature and duration of force applied by the vehicle wheel to the pavement/sensor complex. This error may reach 40% for polymer sensors and 7% for quartz, and strain gauge and bending plate sensors (Burnos and Gajda 2016, Burnos and Rys 2017).

The effect of inaccuracy of Weigh-in-Motion systems on axle load spectra (ALS)

Axle load spectra express percentage of axles falling within a given interval of axle load. Due to WIM system errors, some axles that have real load in the load interval i are assigned to invalid load intervals k, where $k \neq i$. Consequently ALS determined on the basis of Weigh-in-Motion data varies from the ALS that would have been determined on the basis of accurate measurements. According to previous works, the effect of WIM systems accuracy on ALS is considered with regard to two error components: systematic and random. To visualise this effect, the following analysis was performed:

1. A sample WIM data set was chosen from a reference WIM system. It was assumed that those original data did not include measurement errors.
2. 6 cases of random and systematic errors were assumed (described in detail in Table 1).
3. Each axle load measurement in the original data set was modified to introduce a controlled error into the measured values, thus creating data sets that included errors.
4. The accuracy of weighing in the systems with introduced errors was assessed based on the values of relative error of axle load and gross vehicle weight measurements.
5. Axle load spectra were obtained on the basis of the original data set and the remaining 5 modified data sets.

The original data set was delivered from a reference WIM station on the Polish national road no. DK46 (GPS coordinates 50.69162N, 18.23691E). The system was calibrated and subjected to constant monitoring, thus providing accurate measurement data. For the purpose of the analysis, it was assumed that the weighing error from this system is close to zero (case 0 in Table 1). For such original data ALS were obtained. The measurements covered the period from 1 August 2018 to 10 October 2018 and included 250 863 records of heavy vehicles. More detailed information about traffic characteristics for this station are available in previous studies (Rys 2019, Rys et al. 2019).

In the next step the original data were modified to simulate weighing errors. For this purpose, measurement error was simulated for each axle load according to formula (1).

$$Q_E^i = C \cdot Q_V^i + \sigma \cdot z \cdot Q_V^i \tag{1}$$

where: Q_E^i – axle load with introduced error, Q_V^i – original axle load assumed to be error-free, C – calibration coefficient, σ – standard deviation, z – random variable with standardised normal distribution N(0,1), i – index of measurement.

In equation (1) C is the calibration coefficient of the WIM system. If $C = 1$, it means that $Q_E^i = Q_V^i$ and the weighing results from the WIM system are the same as the original axle load assumed to be error-free. If C is greater than 1, the results from the WIM system are overestimated, and if C is less than 1, they are underestimated relative to the true values of axle load. Calibration coefficient $C \neq 1$ thus enables introduction of an error having the characteristics of a systematic (bias) error into the weighing results.

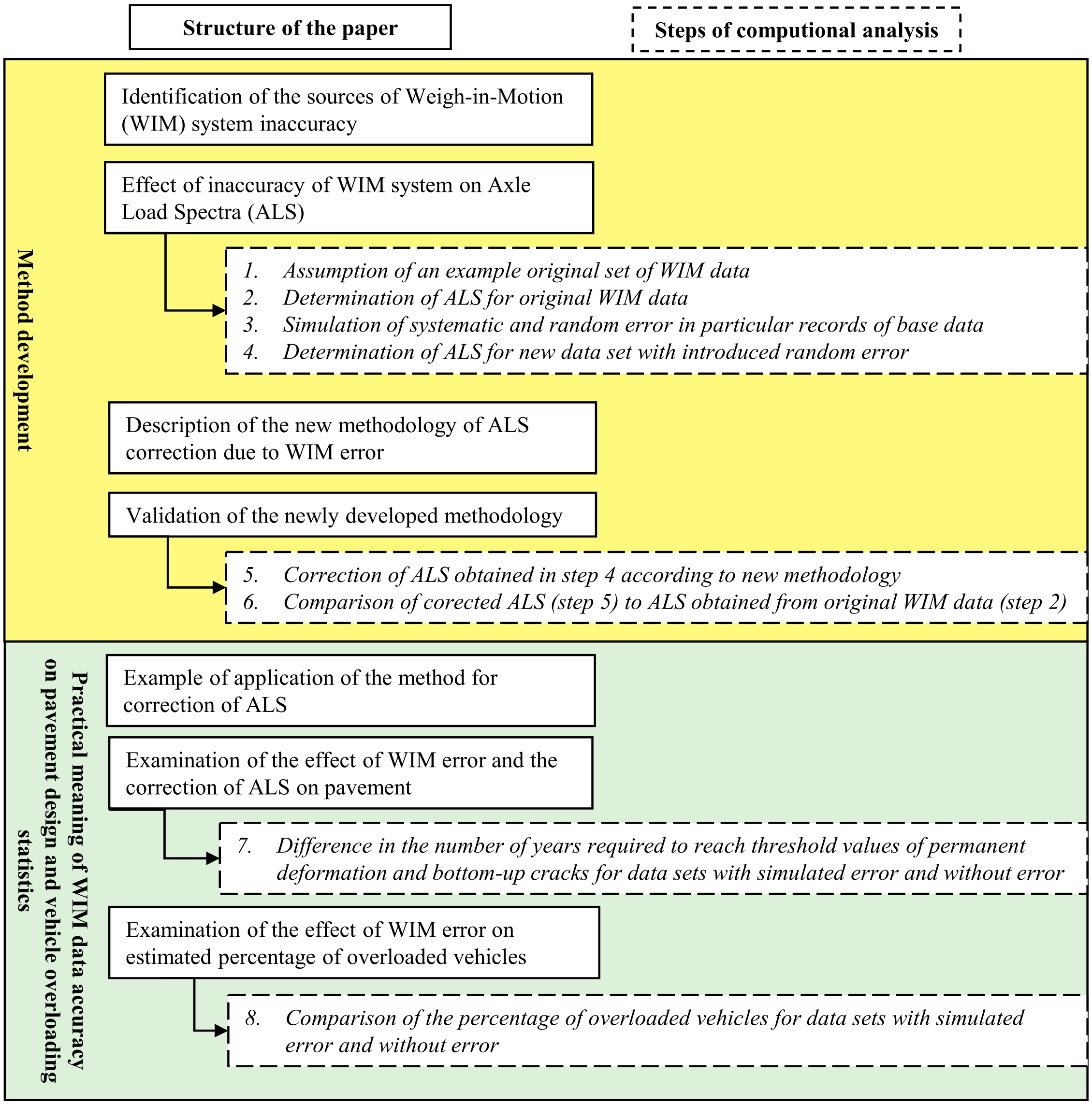


Figure 1. Flowchart of the analysis performed to develop and validate the new methodology of axle load spectra (ALS) correction and its meaning for pavement design.

In turn, component $\sigma \cdot z \cdot Q_V$ in the equation (1) allows to add a random element to the weighing results from the WIM system and thus simulate random errors.

The two components introduced into the weighing results by equation (1) cause the total weighing error in the WIM system. While this weighing error can be estimated in various ways, the starting point for its estimation is always the absolute relative error of a single measurement defined by (2)

$$\delta^i_{\text{abs}} = \left| \frac{Q^i_E - Q^i_V}{Q^i_V} \right| \tag{2}$$

A $\delta_{0.95}$ error was used to assess the accuracy of the weighing results, which is defined on the basis of reliability characteristics:

$$\Phi(\delta^{\text{abs}}) = 1 - P(\delta^{\text{abs}}) \tag{3}$$

where:

$P(\delta^{\text{abs}})$ – cumulative distribution function, δ^{abs} – random variable, whose realisations are constituted by the absolute relative error values (2).

The characteristic (3) is called system reliability characteristic and determines the probability of the occurrence of a weighing error with a value greater than δ^{abs}. Based on this characteristic, we can also distinguish an error $\delta_{0.95}$ with a value corresponding to the probability of occurrence $P =$

Table 1. Cases of errors introduced into original data.

Case no.	Error coefficient		Relative error of WIM	
	calibration coefficient C	standard deviation σ	$\delta_{95\%}$ Axle	$\delta_{95\%}$ GVW
0	1	0	0	0
1	0.9	0	0.104	0.1
2	1.1	0	0.104	0.1
3	1	0.05	0.097	0.045
4	1	0.09	0.176	0.081
5	1.05	0.05	0.131	0.087

0.05. This means that the error $\delta_{0.95}$ is such a value of the function argument (3), for which probability takes a value of 0.05 i.e. $\Phi(\delta_{0.95}) = 0.05$.

Table 1 summarises five different cases of errors considered in the analysis and the case '0' where error does not occur (original data from the reference WIM system). On the right side of the table, $\delta_{0.95}$ error was calculated for measurements of axle load and GVW (Gross Vehicle Weight).

In order to visualise the impact of the introduced weighing errors on the shape of the ALS, the weighing results of the first axle of reference vehicles were analysed (five-axle truck with three axle semi-trailer). Load of the first axle of such vehicles has a much lower standard deviation in comparison to other vehicles and its load depends on gross vehicle weight (GVW) to a lesser degree (Nichols et al. 2009, Burnos and Gajda 2016, Bunnell et al. 2018). Therefore, the shape of ALS of this axle is close to normal distribution and can be easily analysed.

The ALS for different cases of weighing errors are presented in Figure 2, which includes spectra of steering (front) axles in trucks with semi-trailers. For clarity of presentation, Figure 2 (A) shows cases 1 and 2 with no random error. Figure 2(B) presents cases 3 and 4 (with no systematic error) as well as case 5 (with both systematic and random error).

In the case of systematic error (see Figure 2(A)), each value of the measured load is shifted due to multiplication of the real value of load by the factor C. The effect of systematic error is presented by some researchers as independent of axle load (Prozzi et al. 2008). When such an assumption is made, systematic error is a constant value for the whole range of axle loads and the shape of the spectrum and the standard deviation is the same as in the basic case 0. In the considered example, the shift depends on axle load and is lower for lighter axles, thus the shape of the spectrum and the standard deviations for cases 1 and 2 differ from the basic case 0. As evident from Figure 2(B), random error causes a diffusion of the original spectra, observed as an increase in standard deviation, and has no effect on the mean value of axle loads. ALS determined for case 5 is a product of concurrent shift and diffusion of the original ALS.

Description of the new methodology of ALS correction due to WIM error

The currently used methods of WIM system calibration reduce the systematic error. Those calibration methods use standard procedures that compare measurements obtained from WIM and from static scales for pre-weighed vehicles. It is commonly assumed that the measurement from static scales represents a true value of axle load. Correction of systematic error in ALS consists in adding the shift value to the values of axle loads delivered from the WIM measurements.

Correction of random error in ALS is more complex. The ALS from static measurement are not determined in practice. Only the static load is known for different axle types based on the truck used in calibration. Therefore, the error is calculated based on WIM measurement and static load for the same axle. Let us assume that true ALS with no errors is known and it is marked in Figure 3 by the grey column series. ALS with no random error corresponds to the spectrum that would be obtained from measurements carried out on accurate static weights. For this spectrum the percentage of axle observations

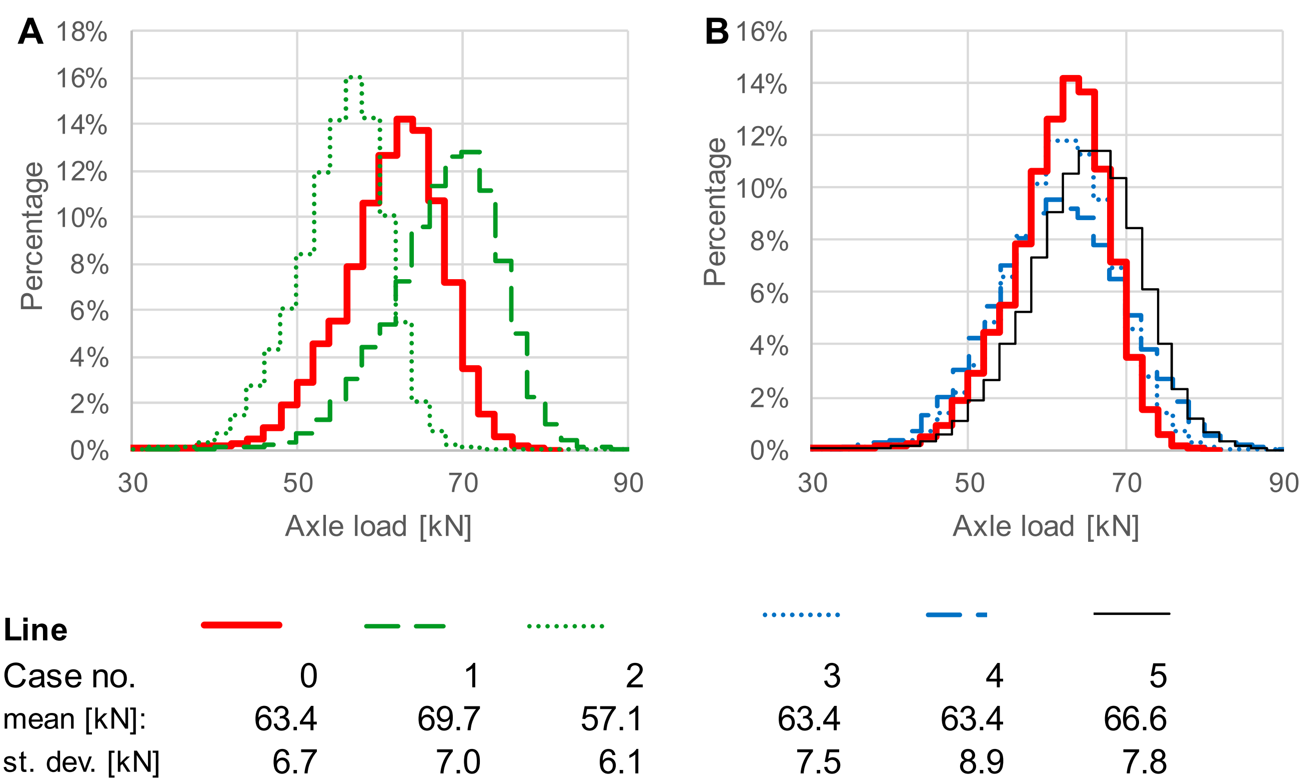


Figure 2. An example of the effect of (A) systematic and (B) random components of relative error on the axle load spectrum (ALS).

in a particular load interval i are marked as s_i in Figure 3 (designation after percentage of *static* weights).

Any deviations from real (static) value of axle load that result from random error cause the measured values to lie beside the real value and if the error is higher than the interval width, the observation will be classified into different load intervals than the correct interval 'i' (see 'red' distribution of random error in Figure 3). It can be assumed that random error has a normal distribution. An example of such error distribution for a sample load interval designated by k is presented in Figure 3 as horizontal red lines series. It is visible that some observations fall into interval k, and other observations fall outside of the interval k. The number of observations in a given axle load interval j is a sum of accurate measurements and inaccurate measurements classified into interval j. Accurate measurements are close to the real value Q_j, differing from the load Q_j so slightly that they fall into the range of the same load interval j. Measurements resulting from all the other intervals of actual values (like interval k) fall within the range of the interval j due to occurrence of random error. Formula (4), which is the probability density function of a normal distribution, is used to calculate the percentage of recorded loads in the interval j coming from axles with real loads Q_k, but classified into interval j due to *random* error r_j.

$$r_{j,k} = \frac{1}{\sigma_k\sqrt{2\pi}} \cdot exp\left(-\frac{(Q_k - Q_j)^2}{2\sigma_k^2}\right) \tag{4}$$

where: $r_{j,k}$ – percentage of observations of loads Q_j delivered from WIM system caused by axles with real load Q_k, σ_k – standard deviation of the axle load Q_k due to random error, j, k – designations of load intervals,

while:

$$\sum_{j=1}^{n} r_{j,k} = 1 \tag{5}$$

When systematic error occurs, it can be included through modification of the Q_k value in formula (4). In the presented study it was assumed that systematic error is linearly proportional to the measured load (see also Equation (1)). For the assumed linear systematic error, the formula (4) is modified into the following form:

$$r_{j,k} = \frac{1}{\sigma_k\sqrt{2\pi}} \cdot exp\left(-\frac{(Q_k/C - Q_j)^2}{2\sigma_k^2}\right) \tag{6}$$

where: C – calibration coefficient, all remaining designations are the same as in formula (4).

For the entire considered range of axle loads, the values of $r_{j,k}$ create a matrix with n rows and columns. The matrix will be designated as R (after *Relative* error). The discrete spectrum of real axle loads can be also expressed by a vector S, within which s_k express percentages of observations in particular load intervals Q_k, in other words – express the actual spectrum of real loads. Analogously, the vector M defines the axle load spectrum obtained from *Weigh-in-Motion* system. For the spectrum (vector) M the total percentage m_j, reflecting all axle load records falling into a given load interval j, is calculated as a sum of measurements coming from all the accurate load spectrum intervals k (k from 1 to n, including $k = j$). The percentage of loads m_j in the interval j in the spectrum obtained from WIM is calculated according to Equation (7).

$$m_j = \sum_{k=1}^{n} s_k \, r_{k,j} \tag{7}$$

The formula (7) for the whole range of axle load intervals n is the same as formula for matrix multiplication. Therefore, the spectrum M is delivered from multiplication of the matrix of relative error R by the accurate load spectrum S:

$$R \cdot S = M \tag{8}$$

The axle load spectrum M delivered from Weigh-in-Motion is known and there is a need to correct it due to random error occurrence. Therefore, accurate axle load spectrum S is delivered from the equation (9):

$$S = R^{-1} \cdot M \tag{9}$$

where: S – corrected axle load spectrum corresponding to the accurate axle load spectrum, R^{-1} – the inverse of matrix of relative error, M – spectrum of axle loads obtained from WIM measurements.

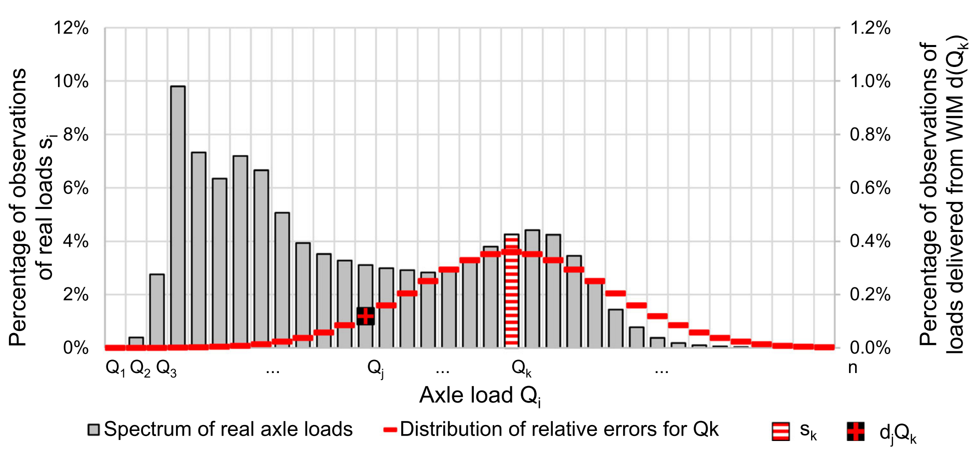


Figure 3. Example scheme of load spectrum and distribution of random errors obtained for mean load Q_k.

Validation of the newly developed methodology

The theoretical explanation requires verification. For this purpose, the previously described vehicle load data sets with simulated measurement errors were used. Sample ALS shown in Figure 4 comprise the spectrum of steering axles of five-axle articulated trucks with semi-trailers (Figure 4(A)) and the spectrum of single drive axles for all vehicles, which is more complex (Figure 4(B)). Figure 4(A,B) both include the following cases of axle load spectra obtained:

1) for the original set of data with no error ($\delta_{95\%} = 0$),
2) for data where both random and relative error was simulated (case 5 in Table 1) and $\delta_{95\%} = 0.131$,
3) for data with simulated error, corrected according to the newly developed method, as described in the previous section.

It is visible in Figure 4 that the calculations resulted in identical axle load spectra obtained for the original set of WIM data and the corrected data set which initially included the simulated error. It confirms that solution presented in Equations (2)–(8) enables elimination of measurement error from axle load spectrum. While the presented verification may seem uncomplicated and obvious, it should be emphasised that square matrices R used in the example consist of 40 rows and columns. Transformation of large matrices can be numerically unstable, even if variables are defined as double-precision floating-point type. The algorithms applied in computer programmes like Excel or Matlab may prove unable to inverse the R matrices with sufficient precision. The problem may manifest itself as fluctuations and unrealistic values on the corrected ALS. An increase in the number of intervals of ALS as well as rounding of numbers in matrices R and S to maximally three decimal places contributes to an increase in stability of the R matrix inversion. The authors used Gauss-Jordan Elimination algorithm for matrix inversion, which provided satisfactory solutions. The matrices R used in the analysis had 40 rows and columns.

Example of application of the method for correction of ALS

The newly developed method of ALS correction makes it possible to estimate the weighing error using a reference (standard) spectrum of steering axle load of a reference vehicle (abbreviated to sSALS) (Jacob et al. 2002, Rys 2019, Burnos and Gajda 2020). From the cited papers it is justified to sSALS is constant on an given area (e.g. Poland) and changes in traffic or WIM site localisation have no effect on it. On the other hand the first axle load distribution spectrum obtained in a specific WIM system will be called measured steering axle load spectrum (mSALS). If mSALS is not equal to sSALS, it means that a measuring error has occured. The error may arise from invalid calibration coefficient C and random error component σ. Substitution of appropriate calibration coefficients C and σ into formula (6) enables determination of the matrix of relative error R. When sSALS is substituted as vector S into Equation (8), then the multiplication of sSALS and the matrix of relative error R delivers vector M, which is approximately equal to mSALS. The appropriate coefficient C and σ can be obtained in successive iterations until the best fit of vector M to mSALS is achieved.

The sSALS was characterised as a normal distribution with mean equal to 55 kN and standard deviation equal to 4 kN, according to previous studies (Rys 2019). A plot of the spectrum is given in Figure 5.

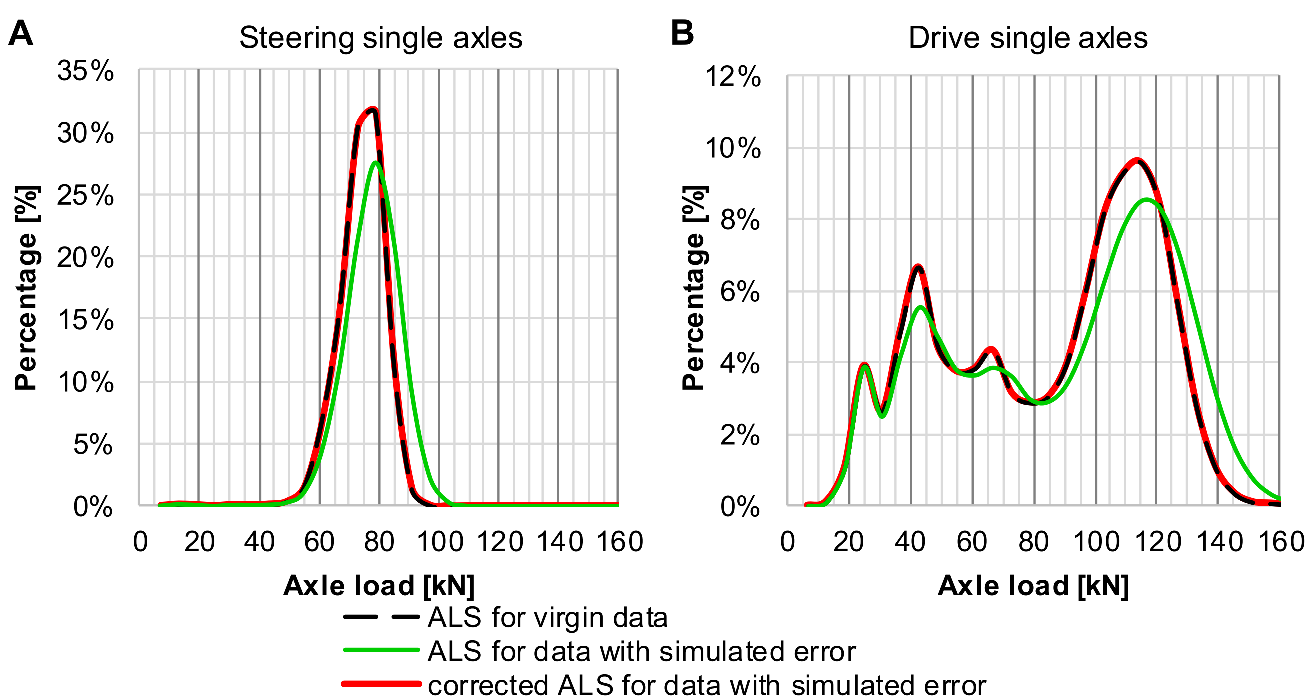


Figure 4. Axle load spectra obtained for (A) steering single axles and (B) drive single axles, with distinction between the three cases: no measurement error as well as simulated measurement error (before and after correction).

In order to better explain the approach, another set of WIM data was used. The data were delivered from the national road DK7 (GPS coordinates 50.39977N, 20.095072E). The measurements covered the period from 1 January 2016 to 10 May 2016. The class of two-axle trucks with triple-axle semi-trailer was chosen as an example to analyse load spectra. The data set included 583 664 records of those vehicles.

Figure 5 shows the mSALS obtained for WIM station DK7, demonstrating the fact that it does not overlap with the standard spectrum sSALS. When error coefficients $C = 0.915$ and $\sigma = 0.03$ are assumed to calculate matrix R, the vector M obtained from Equation (8) achieves the best fit to mSALS, thus the assumed coefficient values describe the error on the considered WIM station.

In order to determine the corrected ALS for other axles in the considered vehicle type (single drive axle and triple axle in trailer) the formula (9) is used. The matrix of relative error M obtained on the basis of adjustment of sSALS to mSALS has to be inversed. The ALS obtained from the measured data is substituted as vector M, and the corrected ALS is calculated from formula (9) as vector S. Figure 6 presents the ALS obtained from data measured on the considered WIM station DK7 and the corrected ALS, with error coefficients of $C = 0.915$ and $\sigma = 0.03$. As it can be concluded from Figure 6, while the axle load increases the difference between ALS from the measured (inaccurate) data and ALS after correction increases. Calibration significantly impact on the estimation of the heaviest axles.

Examination of the effect of WIM error and the correction of ALS on pavement design according to M-EPDG approach

The Mechanistic-Empirical Pavement Design Guide (M-EPDG) uses ALS as one of several traffic data input. The uncertainty of ALS can be a source of inaccurately predicted pavement fatigue life. The following example calculations were performed to evaluate how random and relative errors of WIM system correspond to predicted time required to reach threshold values of flexible pavement distresses. The AASHTOware (version 3.1) software was used for this purpose. The flexible pavement structure with a moderate thickness of asphalt layers was assumed for analysis and it is presented in Figure 7. The structure was designed according to the Polish

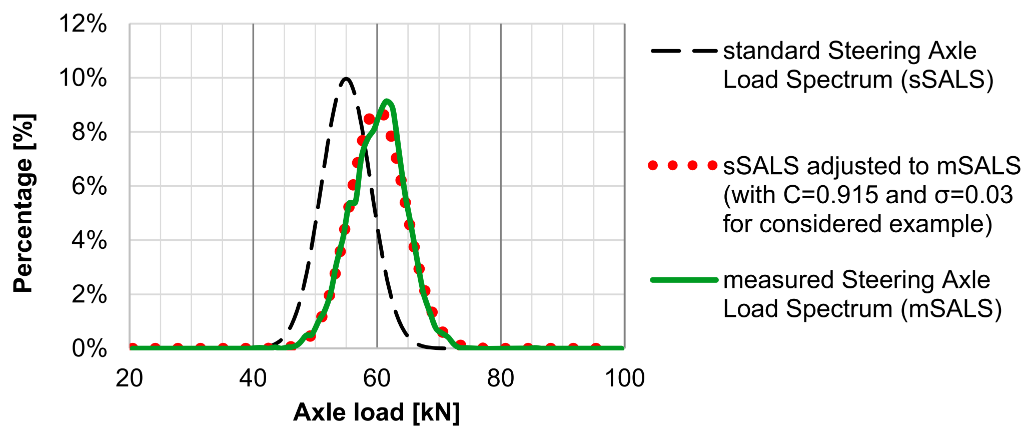


Figure 5. Plot of sSALS spectrum adjusted to mSALS in order to determine the error components C and σ.

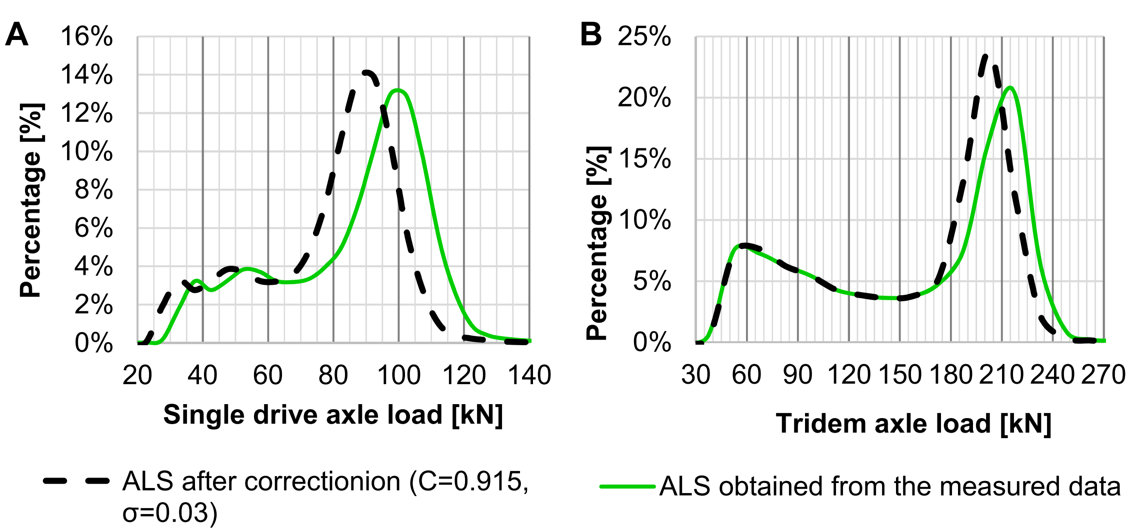


Figure 6. Axle load spectra (ALS) obtained from the measured data before and after correction for A) drive axles and B) tridem axles.

Catalogue of Flexible and Semi-Rigid Structures and correspond to moderate structure described in previous section. Threshold values were assumed according to Polish requirements given in the Diagnostic of Pavement Conditions system and equalled: 5% of cracked lane area, 20 mm of total rut depth and terminal IRI = 4.3 mm/m. Distresses were calculated with 80% reliability. Annual average daily traffic was assumed as 1300 vehicles per design lane and the yearly growth rate was assumed as 3%. Traffic statistics including vehicle class distribution and number of axles per truck were assumed according to WIM data used in this paper. While all variables and input data remained constant, axle load spectra as traffic input data related with random and relative error of WIM system varied according to cases from 0 to 5, described in Table 1.

The temperature data were collected and analysed on the basis of meteorological station located near city Lodz in the central of Polish territory (GPS coordinate: N 51.756 E 19.444). The data were collected from period equalled 23 years from 1 January 1994 to 31 December 2017. The climatic conditions are characterised by mean annual air temperature 8.7°C and freezing index 266.9°C-days. The performance grade determined for wearing course and reliability 80% in this region equals PG 52-22 (Pszczoła et al. 2017).

The master curves of particular asphalt mixtures used for wearing course, binder course and asphalt base assumed on the level 1 according to previous studies (Rys et al. 2019). Remaining design properties of asphalt layers are summarised in Table 2. The base was made from unbound materials characterised by annual average resilient modulus given in Figure 7. For all distress models the default calibration factors were used.

Figure 8 presents results of predicted bottom-up cracks and permanent deformation in 30 years period of analysis. Because terminal IRI threshold value has not been reach in any case, the charts are omitted. For a reference case 0 pavement reaches threshold level of bottom-up cracks after 24 years of service. Analogously after 8 years of service total permanent deformation reaches assumed threshold value of 20 mm. Case 1 shows that underestimation of axle loads by 10% results in longer estimated pavement fatigue life by around 6 years. It means that if pavement would be design with incorrect ALS data, where axle loads are underestimated, the critical level of pavement failures would appear earlier that it was predicted, what will lead to earlier rehabilitation costs. On the other hand, overestimation of axle loads, as it is expressed in cases 2 and 5, results in some reserve in predicted fatigue life of pavement structure. The reserve equals from 1 to 5 years for considered cases. According to results performed for cases 3 and 4 random error has a minor effect on predicted pavement performance when $\sigma < 0.09$. Analysis also indicates that bottom-up cracking criteria are more susceptible to errors in ALS than permanent deformation criteria. These results prove that correction of ALS on the basis of the methodology developed in this paper can make predicted pavement performance more realistic.

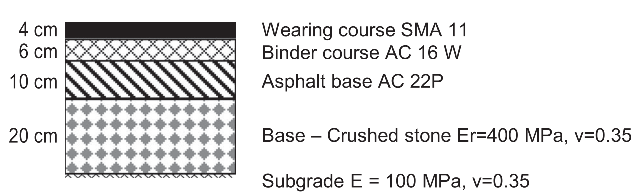


Figure 7. Pavement structure assumed for M-EPDG analysis.

Table 2. Selected properties of asphalt layers.

Layer	Mixture designation	Asphalt binder (EN standard/PG)		Air voids [%]	Effective binder content v/v [%]
Wearing course	SMA 11	45/80-55	PG 76-22	3	16
Binder course	AC 16 W	35/50	PG 70-22	6	11
Asphalt base	AC 22 *P*	35/50	PG 70-22	7	10

Effect of WIM error and the correction of ALS on percentage of overloaded vehicles

Overloaded vehicles occur less frequently than properly loaded vehicles, but due to their greater potential to cause damage they may significantly contribute to pavement distress. The phenomenon of vehicle overloading also has an adverse impact on road safety and fair competition on the transport market (Budzyński et al. 2017). Percentage of overloaded vehicles in total number of trucks (OV), which is a commonly used statistic characterising the scale of the problem, is based on data obtained from Weigh-in-Motion systems. Any inaccuracy in the source data leads to incorrect statistics and may result in inadequate actions taken to prevent overloads.

A vehicle is treated as overloaded in the following cases:

- the vehicle gross weight is greater than the legal limit;
- the load of a single, tandem or tridem axle is greater than the legal limit;
- both the gross weight and the axle load are greater than the legal limits.

The mixed cases mentioned above and the fact that legal limits for axles depend on the position of the axle and its distance to neighbouring axles make it impossible to calculate OV directly from axle load spectra. For the purpose of OV calculations, each vehicle in the data set has to be checked in terms of its overloading. Figure 9 presents the OV values calculated based on 5 cases of data sets with simulated measurement errors and the set without error (case 0). Classification of a particular vehicle to the group of overloaded vehicles was based on the legal axle load and weight limits given in the European Union Council Directive 96/53/EC (the Council of The European Union 1996). For the considered set of original data the percentage of overloaded vehicles equals 28.5%.

Based on Figure 9, it can be concluded that systematic error significantly affects the determination of the percentage of overloaded vehicles OV. When axle loads are underestimated by 10% ($C = 0.9$), the calculated percentage of overloaded vehicles equals 6%, which is an underestimation of by as much as 22 percentage points. Similarly, when axle loads are overestimated by 10% ($C = 1.1$), the calculated percentage of overloaded vehicles equals 43.8%, that is 15.3 percentage points more than the real value. As shown by the results, random error has minor impact on the statistic of overloaded vehicles when $\sigma < 0.09$.

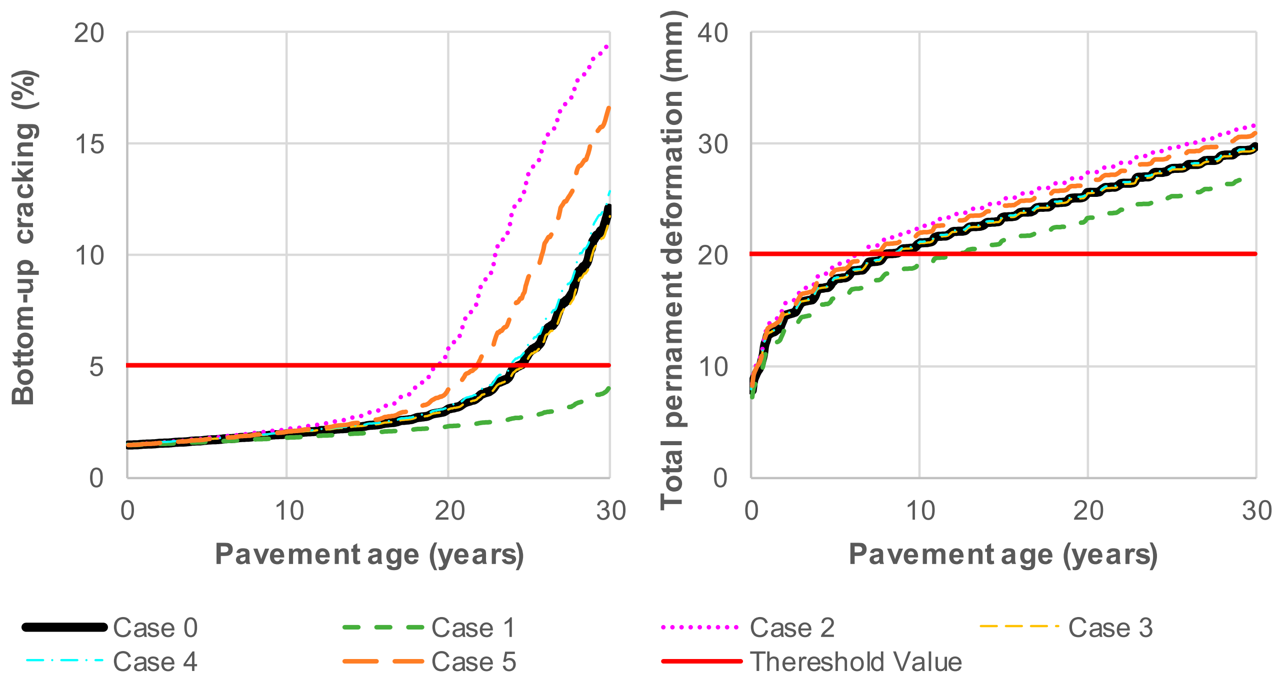
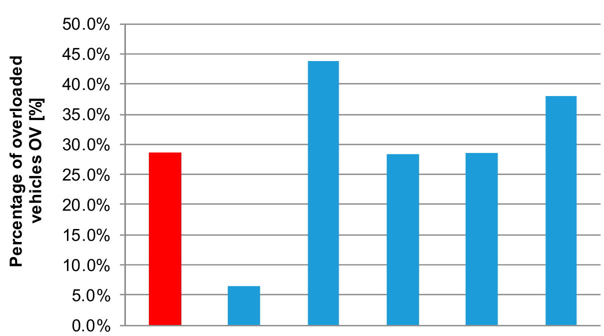


Figure 8. Effect of random and systematic error of axle load measurement on the predicted (A) bottom-up cracks and (B) permanent deformation for sample flexible structure.



Case no.	0	1	2	3	4	5
Coefficient of systematic error C:	1	0.9	1.1	1	1	1.05
Coefficient of random error σ	0	0	0	0.05	0.09	0.05

Figure 9. Effect of random and systematic error of axle load measurement on the estimated percentage of overloaded vehicles.

Summary

(1) The new method of correction of inaccurate axle load spectra obtained from Weigh-in-Motion was developed. The method enables introduction and control of both systematic and random error component effects on axle load spectra.

(2) Full agreement was obtained between the original data and the corrected data (after introduction and control of measurement error). The proposed method produced encouraging results.

(3) The analysis confirmed the significance of axle load measurement accuracy in pavement design. Systematic error component has a more significant effect both on the estimated design traffic, predicted pavement performance and the calculated percentage of overloaded vehicles than the random error component. When axle loads are underestimated by 10% ($C = 0.9$) the threshold values of distresses may appear several years earlier than they were predicted.

(4) When random error remains on low level and the coefficient $\sigma < 0.05$, its effect on the predicted traffic to failure and on the calculated percentage of overloaded vehicles is negligible.

(5) While the values of $\delta_{95\%}$ relative error for axle load estimation are similar, the effect of error on the calculated pavement fatigue life can differ significantly. Therefore, the values of $\delta_{95\%}$ are not valid for assessment of data quality in terms of their application for pavement design.

(6) An important practical advantage of the proposed method is its potential for use in correction of axle load spectra for pavement design and prediction of pavement distresses make analysis results more precise and reliable.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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