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CALIBRATION OF WEIGH-IN-MOTION SYSTEMS – METROLOGICAL ASSESSMENT OF METHODS FOR DETERMINING REFERENCE VALUES

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Abstract

The increasingly common practical application of systems for the dynamic weighing of vehicles in motion makes necessary periodic assessment of correct operation of such systems and calibration of the results obtained from them. This paper presents an experimental study and the obtained measurement results which allow for the determination of reference values essential for the calibration process. It was assumed that Weigh-In-Motion (WIM) systems will be calibrated using the pre-weighed vehicle method. The desired reference values in this case are thus gross weight (Gross Vehicle Weight – GVW) and static load of individual test vehicle axles used in the calibration process. The experiments and analysis of results obtained from them presented in this work involve the use of a platform scale for determination of GVW, as well as portable scales or a dynamic low-speed scale (LS-WIM), intended for measurement of the loads of individual axles of vehicles. All of the scales used in the experiments have valid certificates of metrological approval. The results obtained indicate the possibility of significant simplification of the procedure while still maintaining the required accuracy. The simplification proposed involves the possibility of abandoning the GVW measurement on the platform scale, instead determining this value by summing up the load measurements of all the vehicle's axles obtained on the LS-WIM scale.

Keywords: Weigh-In-Motion systems, calibration, pre-weighed vehicle method, reference values.

1. Introduction

Systems designed for dynamic weighing of vehicles in motion called WIM (*Weigh-In-Motion*) systems have gained popularity in recent years. The root cause of this is the sharp increase in the amount of goods and numbers of people being carried by means of road transport and the subsequent increase in vehicle traffic. This phenomenon is seen in every country in Europe and results in a need for development of systems for controlling the weight of vehicles and for the effective elimination of overloaded vehicles from road traffic. Elimination of overloaded vehicles will consequently ensure effective protection of the road infrastructure and the natural environment, an increase in road safety, and protection of fair conditions of competition among carriers. Simultaneously, there have been advances in the technology of the load sensors used

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in WIM systems [1, 2], procedures for minimizing the influence of external factors have been developed [3, 4] and the accuracy of measuring intermediate quantities, such as vehicle speed, has been improved [5]. In turn this has led to an increase in accuracy [6] and the practical implementation of WIM systems for direct mass enforcement.

The basic load sensors currently used in WIM systems are quartz sensors using the piezoelectric effect [7], linear strain gauges [8] and capacitive sensors [9]. Fibre optic sensors are being used more and more often [10–12].

WIM systems operating in the direct mass enforcement mode should have high and, above all, constant accuracy. In [13] a recommendation was made that the accuracy of WIM systems operating in the direct mass enforcement mode should be no worse than Class A(5). This means that the accuracy of *Gross Vehicle Weight* (GVW) measurement is required to be no worse than 5%, and the accuracy of single axle load measurement is no worse than 8%. However, it must be remembered that weighing accuracy directly affects the effectiveness of eliminating overloaded vehicles from traffic. For this reason, in [14] the authors proposed that the accuracy of GVW measurement should be no worse than 2%.

Ensuring the required accuracy of WIM systems is achieved through their periodic calibration. The literature describes various methods and algorithms used at the calibration stage of WIM systems [15].

Conversely, the increase in the number of WIM systems, in particular those used to directly eliminate overloaded vehicles from road traffic, has resulted in the need for periodic metrological inspection and calibration of a large number of WIM systems. For this reason, metrological control and calibration must be conducted in an effective manner, namely by minimizing the time and cost inputs for the procedure applied [16].

Two methods have dominated the calibration methods of WIM systems for years. Both are based on the comparison of vehicle weighing results obtained from the WIM system with the weighing results of the same vehicles in static conditions, on a reference scale. The first method to be mentioned is the pre-weighed vehicle method [13]. This involves the appropriate selection and weighing of several test vehicles on a reference scale in order to determine their GVW and the static loads of individual axles, which are then taken as reference values. Next, these same vehicles perform several runs through the tested WIM station. System errors are determined by comparing the results of weighing on the reference scale with the results obtained from the WIM system. The number and parameters of the test vehicles and the metrological parameters of the reference scale are defined in relevant documents [17].

In the second method, vehicles are selected from the traffic stream vehicles that have passed through the WIM station. These vehicles are then directed to a static scale [18]. The required number of measurement results depends on the accuracy of the calibrated WIM station. In [19], for example, it was found that for the WIM system to an accuracy of 1%, 400 calibration measurements are required.

In [20] three WIM system calibration methods are listed as commonly used in practice. These are the previously described pre-weighed vehicles method, the utilization traffic stream vehicles of known static weight method and WIM data *quality control* (QC) techniques. QC techniques involve comparing the distribution of measurement results, *e.g.* the first axle load or GVW of five-axle vehicles, with the pattern of these distributions, previously registered in the same WIM system. Observing a significant change in these distributions indicates the need to calibrate the system.

The calibration method using vehicles of known mass (pre-weighed vehicles or traffic stream vehicles) is described in detail in ASTM Standard E1318-09 [21].

The issue of calibration and accuracy assessment of WIM systems is also described in [22]. This paper presents recommendations for correct calibration of the WIM system, taking into account the impact of a limited number of test runs, the impact of temperature, speed, and vehicle class on measurement errors.

Of course, there is no perfect method for calibrating WIM systems. The limitations of the calibration method based on pre-weighed vehicles or traffic stream vehicles result from errors in the static weighing of these vehicles. The uncertainty in determining their total mass and axle loads is transferred to the uncertainty of the calibrated WIM system. This problem is described in [23].

Attempts have been made to practically apply other calibration methods, such as the use of an instrumented vehicle. However, due to the high cost of this method, it has not found wider application in practice [24].

Additionally, methods are proposed to continuously monitor the reliability of weighing results in WIM systems. In [25, 26] the use of an algorithm with fuzzy logic to assess the reliability of weighing results was proposed. Two groups of factors affecting accuracy were taken into account. The first group are meteorological factors. The second group consists of factors determining the correctness of driving through the WIM station (trajectory, constant speed). The practical implementation of the proposed algorithm showed that almost 80% of the weighing results can be considered reliable.

The error analysis of WIM systems is presented in [27]. In particular, the quantitative impact of calibration on weighing errors was determined for various sensor technologies (load cell, bending plane, quartz sensor). As a result of calibration of the WIM system, the bias error and standard deviation of the weighing results were reduced by approximately 5 times.

The presented literature review shows a fundamental conclusion: the basic method of calibrating WIM systems is the method using vehicles of known mass passing through the calibrated station. Monitoring the reliability of weighing results by assessing the trajectory of the weighed vehicle through the WIM station or by observing changes in the distribution of measurement results of selected values (steered axle load) will not replace calibration. These methods only allow you to eliminate weighing results that are not sufficiently reliable or predict the need for calibration.

Maintaining high and constant accuracy of WIM systems operating in the direct mass enforcement mode is achieved primarily through their frequent calibration. However, the influence of environmental factors causes this accuracy to change over short periods of time. Therefore, regardless of the calibration performed, attempts are made to reduce this sensitivity. In [28] a method for correcting the influence of temperature on vehicle weighing results in WIM systems equipped with ceramic piezoelectric sensors was presented. The disadvantage of these sensors is high temperature sensitivity. However, they have their advantages, including high sensitivity and wide frequency characteristic. The results of similar studies were also presented in [29].

An alternative to calibration carried out using pre-weighed vehicles or traffic stream vehicles is the auto-calibration of WIM systems. Autocalibration algorithms have been described in [30–32]. The results presented in these papers confirm the effectiveness of such calibration. In particular, the ability of the auto-calibration algorithm to compensate for the influence of temperature on measurement accuracy was demonstrated. In [31] and [32] the load of the first axle of a selected class of 5-axle vehicles was used as a reference value in the auto-calibration process. The load of this axle is also used by other researchers as a reference value in the process of continuously monitoring the accuracy of the WIM system [33].

The results of testing the auto-calibration method combined with automatic identification of characteristic vehicles are presented in [34]. The presented results confirm the effectiveness of this solution.

Also, in [35] the auto-calibration method was used to correct weighing results in WIM systems. The method was implemented in South Africa in 2008. It uses the steer axle load of six-axle and seven-axle vehicles as reference values. These vehicles are additionally filtered not only by the number of axles but also by the distance between subsequent axles.

It should be emphasized, however, that from the point of view of legal metrology and type approval procedures, the recognized and recommended calibration method is the pre-weighed vehicle method and the stream traffic vehicle method. The auto-calibration method cannot be used during legal metrological control of WIM systems operating in the direct mass enforcement mode.

From the description of the pre-weighed vehicles method, as well as traffic stream vehicles method presented here, it can be seen that the calibration of the system is fairly demanding in terms of logistics. Apart from the test vehicles, a vehicle scale of required accuracy is needed (with a certificate of calibration) which not only is capable of measuring the gross vehicle weight but also the static load of each individual axle. There are no vehicle scales which enable the direct measurement of both values simultaneously. For this reason, two scales are generally used; a platform scale for the direct measurement of the GVW (the measurement takes place in static conditions) and a dynamic *low-speed scale* (LS-WIM) used often for the direct measurement of loads of individual axles. The LS-WIM scale also makes it possible to determine GVW by summing up the load measurements of all of the axles of the test vehicle. The value determined in this manner is called the total weight in order to differentiate it from the GVW measured directly on the platform scale. The GVW value determined on the platform scale and the values of individual axle loads of the test vehicles are taken as reference values. Using these values, the calibration errors of the WIM system are determined. The method for determining the reference values of individual axle loads and axle group loads are described in detail in [17].

It is also possible to use portable scales in the process of determining the reference values; these scales are placed under the wheels of the vehicle. The measurement is taken in static conditions at a site with precisely defined geodesic parameters (longitudinal and lateral inclination of the site). In this case, the load value of a selected axle can be determined by summing up the load values of all the wheels of this axle. By summing up the load values of all the axles of the vehicle, the *total weight* (TVW) interpreted as an estimate of the GVW, can be calculated. In this experiment, the best solution is to use as many scales as the weighed vehicle has wheels. This prevents unwanted transfer of weight between individual wheels and axles of the vehicle.

The advantage of portable scales is that their accuracy can be checked immediately before use in field measurements. This checking is done at a specialist laboratory using special weight machines of high accuracy. This operation is considerably simpler than checking the accuracy of the other two types of scales *i.e.* platform scale and LS-WIM. Checking the accuracy of a platform scale is much more complicated and is done during legalisation of the scale (initial or re-legalisation) in a two-year cycle. In the period between successive legalisations, it is assumed that the scale maintains its properties if no event takes place which would suggest a need to verify the accuracy of the scale again. Additionally, both the platform scale and the LS-WIM should be accessible in the vicinity of the WIM station being calibrated, for logistical and economic reasons, as well as to avoid excessive fuel consumption by the test vehicle. At many WIM sites, it may be quite difficult to meet these conditions.

High consistency of weighing results on the LS-WIM scale and on portable scales was confirmed in [36]. However, we cannot agree with the authors of this paper that the use of portable scales is particularly difficult because it requires separate weighing of subsequent axles. Appropriate arrangement of the measuring station, as shown in the photos included in this work, allows for simultaneous measurement of the loads of all axles. An additional benefit resulting from such measurement is the elimination of the phenomenon of mass transfer between individual axles. This mass transfer may lead to an incorrect determination of the reference GVW value.

The aim of the study described here was to answer the question of whether it is possible to simplify the WIM system calibration procedure while still maintaining accuracy. This simplification could involve abandoning the measurement of GVW on the platform scale and replacing it with the *total weight* (TVW) determined based on the results of measurement of axle load on an

LS-WIM scale. To this aim, an assessment was conducted of the accuracy of determination of reference values for GVW, TVW and axle load using three kinds of scales: a platform scale, an LS-WIM scale, and portable scales. All the scales used in the experiments held valid certificates of metrological approval.

Based on the experiments conducted, static characteristics of the platform scale and the LS-WIM scale were determined, as was the error of both scales. The reference point constituted the values obtained using the portable scales. The results presented in this paper allow for the formulation of the following basic conclusion: the use of only the LS-WIM scale for determination of reference values used as a reference for the errors of the calibrated WIM system is possible (for some accuracy classes of WIM systems). In the case under consideration, errors of reference values were determined in this manner in the context of calibration of a WIM system of accuracy Class B+(7) [13].

The paper is organised as follows: the Section 2 includes a description of the vehicle scales and test vehicles used during the experiments. The Section 3 presents the results of the measurements and an analysis which aimed to establish the accuracy of the determination of all reference values. The Section 4 includes a summary and conclusion which can be drawn from the study.

2. Description of the experiment

The experiment conducted involved the weighing of five vehicles of different construction types, number of axles, and GVW. The characteristic parameters of these vehicles are presented in Table 1.

Table 1. Parameters of test vehicles used in the experiments.

Item	Vehicle class	Number of axles	Permissible gross weight [kg]	GVW [kg]	Length [cm]	Multiple axle
1.	2-axle lorry (2-axle)	2	16000	8008	620	No
2.	2-axle bus (Bus)	2	3500	3492	590	No
3.	3-axle lorry (3-axle)	3	24000	22096	720	Double axle
4.	2-axle tractor + 3-axle trailer (5-axle_A)	5	40000	40061	1290	Triple axle
5.	2-axle tractor + 3-axle trailer (5-axle_B)	5	40000	30580	1290	Triple axle

The selection of test vehicles ensured a wide range of values to be measured both in terms of static axle load and gross weight. The individual axle load of the vehicles ranged from 1700 kg to 11500 kg, and GVW values from 3500 kg to 40000 kg.

The vehicles were weighed on three scales which differed in their intended use, construction solutions and accuracy. The parameters of these scales are presented in Table 2.

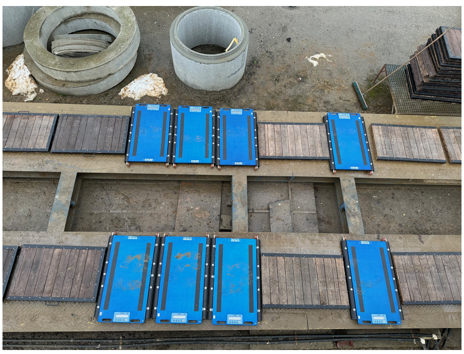
In the first stage of the experiment, GVW and static load of all wheels of all test vehicles were measured simultaneously on the platform and on portable scales. Ten identical portable DFW scales with parameters described in Table 2 were used in the experiment, because the maximal number of wheels in test vehicles is 10 (a 5-axle vehicle). The portable scales were arranged on the platform scale which was then reset to zero. The construction of the platform scale (Fig. 1) ensured the correct operation of the portable scales. After the vehicles were driven onto the portable scales, the measurements from the platform scale and from each of the portable scales were recorded. The

Table 2. Parameters of vehicle scales used in the experiments.

Item	Type of scale	Manufacturer	Accuracy class	Measurement range [kg]	Scale interval [kg]	Vehicle speed [km/h]
1	DFW portable scale	Dini Argeo	III[1]	10000	5 (ext.: 0.5)[2]	N/A
2	Platform scale	WITWAG	III[1]	400–60000	20	N/A
3	LS-WIM scale, type VM 1.2	TENZOVAHY – the Czech Republic	D2[3]	400–20000	20	1–6

[1)] This class concerns the so-called non-automatic scales (usually industrial scales), its accuracy is described by the value of the verification scale interval – in this case ±20 kg (this value depends to the range of scale and maximal number of intervals). [2)] The abbr. *ext.* means that the scale is an extended displaying device. Such a device, following a manual command, temporarily changes the actual scale interval to a value less than the verification scale interval. [3)] Accuracy Class D2 means that the gross weight of the vehicle is indicated with an error no greater than 2%, and that the static individual axle load is indicated with an error no greater than 4% [17].

measurement from the platform scale allowed for the determination of the GVW of the vehicle ($GVW_{platform}$), while the measurements from the portable scales allowed for the determination of the static load of each wheel. The sum of the loads of wheels from one axle was assumed as the static load of that axle, and the sum of the loads of the axles was assumed as the total weight of the vehicle ($GVW_{portable}$). In order to facilitate the placement of the weighed vehicle, wooden platforms and ramps were placed between the portable scales (Fig. 1).



(a)

(b)

Fig. 1. Arrangement of the station for simultaneous weighing of vehicles on the platform scale and portable scales.

In the second stage of the experiment, the test vehicles were weighed on an LS-WIM scale with parameters as described in Table 2. This low-speed scale (LS-WIM) allowed for the measurement of dynamic loads of individual axles of the vehicle but the speed of the weighed vehicle could not exceed 6 km/h. Assessment of the static load and the errors of this scale was conducted based on the weighing results of all five test vehicles. Each vehicle completed five runs across the tested scale, in the same direction. The measurement result of the static load of each axle was calculated as the mathematical mean value of the results obtained in successive runs (Fig. 2), and the total weight GVW_{LS} was calculated as the sum of the mean values all axle loads determined in this manner.

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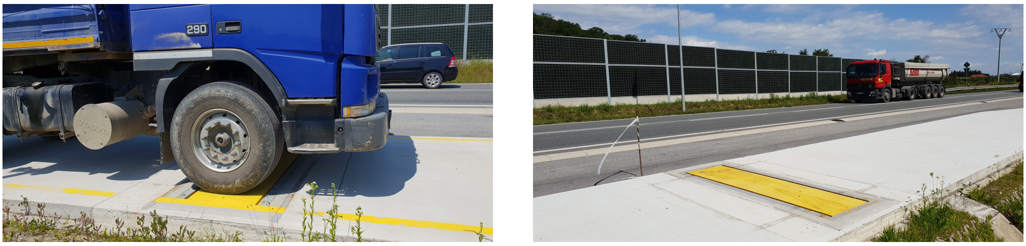

(a) (b)

Fig. 2. Weighing the vehicles on the low-speed scale (LS-WIM).

3. Analysis of measurement results

The measurement results obtained by using the portable scales and the platform scale are presented in Table 3.

Table 3. Results of the measurement of axle loads and GVW of the test vehicles, using portable and platform scales.

Axle number	**Vehicle class – Axle load [kg]**				
	2-axle	Bus	3-axle	5-axle_A	5-axle_B
1	4667.5	1666.5	6375	7059	6547
2	3340.5	1825.5	7765	11584	7562
3	×	×	7956	7231	5570
4	×	×	×	7026	5489
5	×	×	×	7161	5412
	Gross vehicle weight – GVW [kg]				
$\text{GVW}_{\text{portable}} = \sum_{i=1}^{5} \text{Axle\_load}_i$	8008	3492	22096	40061	30580
$\text{GVW}_{\text{platform}}$	8540	4020	22700	40700	31100
$\text{GVW}_{\text{corrected}}$ defined by (2)	8005	3495	22133	40092	30514
	Relative error				
δ – relative error [%]	6.6	15.0	2.7	1.6	1.7
$\delta_{\text{corrected}}$ [%]	0.04	0.08	0.17	0.08	0.22

The relative error was defined according to formula: $\delta = \dfrac{\text{GVW}_{\text{platform}} - \text{GVW}_{\text{portable}}}{\text{GVW}_{\text{portable}}} 100\%$.

As the portable scales were verified in the laboratory immediately before the experiment using precise mass standards, their measurement results of axle load and the total weight values ($\text{GVW}_{\text{portable}}$) calculated from them were assumed as the reference values for assessment of the errors of the two other types of scales, that is, the platform scale and the LS-WIM scale. During laboratory verification of portable sales, all of them have the accuracy better than the nominal value of verification scale interval, *i.e.* 5 kg.

Based on the results obtained, static characteristics of the platform scale were determined (Fig. 3a).

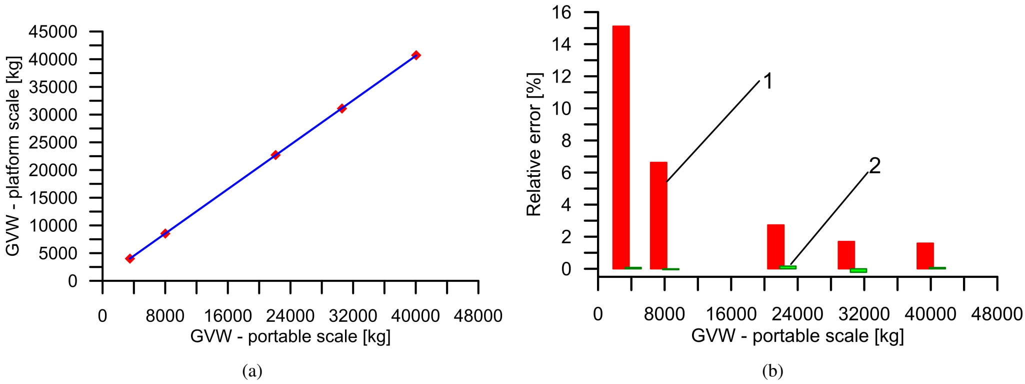

Fig. 3. Metrological characteristics of the platform scale. a) – static characteristic, b) – errors of the scale before correction (1) and after correction (2).

The linear model describing these characteristics, determined using the least squares method, takes the form of (1).

$$GVW_{platform} = 1.0023 \cdot GVW_{portable} + 517.15 \text{ kg}, \tag{1}$$

where: $GVW_{platform}$ – the result of GVW measurement on the platform scale, $GVW_{portable}$ – the total weight calculated on the basis of measurement of the static axle load on the portable scales.

From the coefficients of this characteristic (1), it can be seen that the platform scale exhibits an offset effect of 517.15 kg. Being aware of these coefficients allows for the correction of the results obtained on the platform scale. The corrected weighing results from the platform scale ($GVW_{corrected}$) were calculated based on the model (1), in line with the formula (2).

$$GVW_{corrected} = \left(GVW_{platform} - 517.15 \text{ kg}\right) / 1.0023. \tag{2}$$

The relative error of the platform scale δ (Table 3) was calculated with reference to the total weight of all reference vehicles ($GVW_{portable}$). The corrected relative error $\delta_{corrected}$ was calculated in the same manner, with the difference of being calculated for weighing results corrected according to the formula (2). The value of this error for individual reference vehicle is approximately 0.2%, suggesting a high conformity of the static characteristics of the tested platform scale with the linear model assumed to describe it. It should be emphasised that this high conformity was sustained across a broad range of measured values (GVW), namely, from 3500 kg to more than 40000 kg. The correction of the measurement results of the LS-WIM scale, that is, the axle load and GVW_{LS}, was conducted in the same way.

The results of weighing the test vehicles on portable scales and on the low-speed VM 1.2 WIM scale (LS-WIM) are presented in Table 4.

The relative error was defined according to formula under Table 3.

On the basis of Table 4 and the characteristics of errors (Fig. 4b), it can be stated that the GVW measurement error of the LS-WIM scale when compared to the portable scales does not exceed 1.2%. The static load of an individual axle determined on the LS-WIM scale contains an error which does not exceed 3.3% when compared to the portable scales (Fig. 5).

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Table 4. Axle loads and GVW of the test vehicles weighed on the portable and LS scales.

Vehicle class	Axle number/GVW	Portable scale	LS scale	Relative error [%]
		Axle load [kg]		
2-axle	1	4667.5	4644	–0.50
	2	3340.5	3340	–0.01
	$\sum_{i=1}^{2} \text{Axle\_load}_i$	8008.0	7984.0	–0.30
Bus	1	1666.5	1660	–0.39
	2	1825.5	1824	–0.08
	$\sum_{i=1}^{2} \text{Axle\_load}_i$	3492.0	3484.0	–0.23
3-axle	1	6375	6493.3	1.86
	2	7765	7723.3	–0.54
	3	7956	7826.7	–1.63
	$\sum_{i=1}^{3} \text{Axle\_load}_i$	22096.0	22043.3	–0.24
5-axle_A	1	7059	7008	–0.72
	2	11584	11540	–0.38
	3	7231	7176	–0.76
	4	7026	7088	0.88
	5	7161	6932	–3.20
	$\sum_{i=1}^{5} \text{Axle\_load}_i$	40061	39744	–0.79
5-axle_B	1	6547	6540	–0.11
	2	7562	7600	0.50
	3	5570	5388	–3.27
	4	5489	5408	–1.48
	5	5412	5284	–2.37
	$\sum_{i=1}^{5} \text{Axle\_load}_i$	30580	30220	–1.18

Table 5 presents the results and weighing errors for multiple axles obtained both from portable scales and from the LS-WIM scale. The maximum error value of results obtained from the LS-WIM scale as determined with reference to the portable scales does not exceed 2.4% (Fig. 6).

Table 5. Weighing errors of axle groups on the low-speed WIM scale (LS) compared to the portable scales.

Multiple axle	**Vehicle class**					
	3-axle		5-axle_A		5-axle_B	
	Portable scale	LS scale	Portable scale	LS scale	Portable scale	LS scale
Double axle	15721	15550	×	×	×	×
Triple axle	×	×	21418	21196	16471	16080
Relative error [%]	–1.09		–1.04		–2.37	

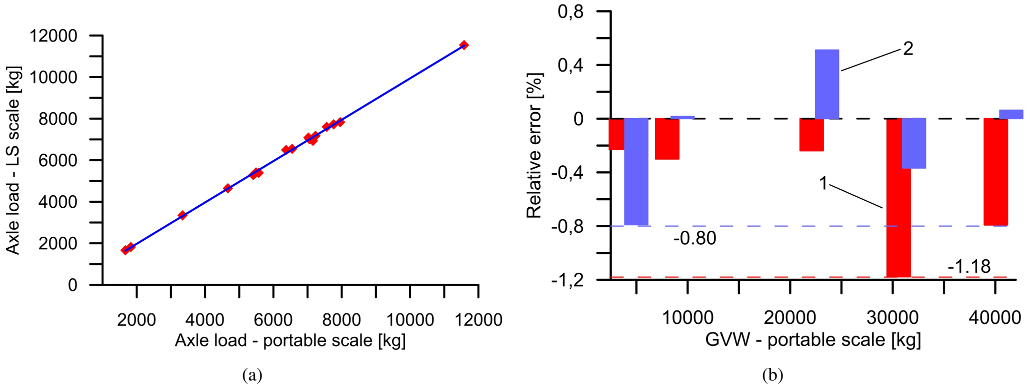

Fig. 4. Characteristics of the low-speed WIM scale (LS). a) – static characteristics, b) – characteristics of the GVW measurement error. 1 – errors before correction, 2 – after correction on the basis of static characteristics.

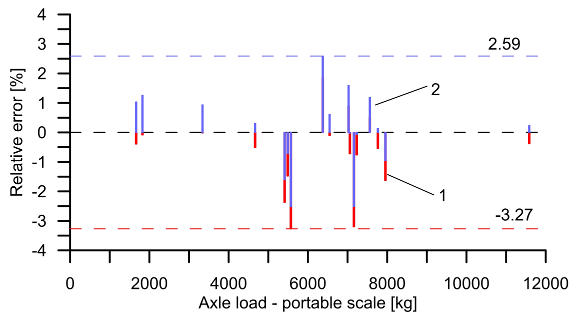

Fig. 5. Weighing errors of individual axles on the low-speed WIM scale (LS) with reference to the portable scales. 1 – before correction of results, 2 – after correction on the basis of static characteristics of the scale.

The static characteristics of the LS-WIM scale are described by (3). This is a result of an approximation of the measurement data, that is, of the results of weighing individual axles or GVW using a linear model. Model (3a) describes the static characteristic of the LS-WIM scale when the subject of measurement is the static axle load. Model (3b), in turn, describes the static characteristic when the subject is the (indirect) measurement of GVW.

$$\text{AxleLoad}_{\text{LS}} = 0.9953 \cdot \text{AxleLoad}_{\text{portable}} - 15.75 \text{ kg}, \tag{3a}$$

$$\text{GVW}_{\text{LS}} = 0.9901 \cdot \text{GVW}_{\text{portable}} + 53.86 \text{ kg}. \tag{3b}$$

The equations show that the static characteristic of the LS-WM scale (3) determined for axle load display a slight shift in zeroes (–15.76 kg) and a gain error of approximately 0.5%. The basis for determining characteristics (3a) and (3b) is the result of weighing each test vehicle five times on the LS-WIM scale. For none of the test vehicles did the relative standard deviation of the axle load measurement results exceed $8.5\ 10^{-3}$, and for the GVW measurement it did not exceed $3.4\ 10^{-3}$. The uncertainty of the weighing results causes uncertainty in determining the coefficients of the static characteristics (3a) and (3b). For characteristic (3), the relative standard deviation of its coefficients is, respectively: for the slope of the characteristic $8.92\ 10^{-7}$ and for the zero shift $3.70\ 10^{-4}$. For characteristic (3b), the relative standard deviation of its slope is $1.11\ 10^{-7}$ and for the zero shift $5.36\ 10^{-6}$.

Deviation of these coefficients from the ideal characteristics (zero offset and slope equal to 1.0) is small enough for the weighing results obtained on the LS-WIM scale not to significantly alter the error characteristics of the scale (Fig. 5 and Fig. 6). In the case of determination of GVW_{LS}, the static characteristic of the LS-WIM scale takes the form (3b). The corrected result is described by the formula (4).

$$\text{GVW}_{\text{LS\_CORR}} = (\text{GVW}_{\text{LS}} - 53.86 \text{ kg})/0.990. \tag{4}$$

After conducting correction on the GVW measurement results, the maximum error value is reduced from 1.18% to 0.80% (Fig. 4b). The distribution of this error in the measurement ranged of the scale is also altered. After the correction, the weighing error of lighter vehicles increased but the weighing error of heavier vehicles significantly decreased. In some applications (*e.g.* elimination of heavy overloaded vehicles from traffic), such an error distribution may have a positive impact.

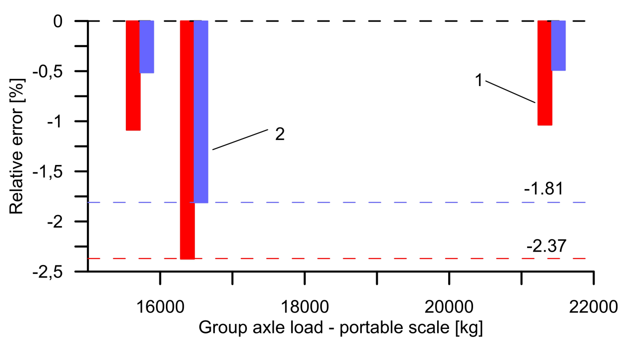

Fig. 6. Weighing errors of axle groups on the low-speed WIM scale (LS) with reference to the portable scales. 1 – before the correction of results, 2 – after the correction on the basis of static characteristics of the scale.

The correction of weighing results of individual axles is also effective. The maximum static load error value decreased as a result of correction from 3.27% to 2.59% (Fig. 5). In the case of multiple axles, the maximum error values before and after correction were 2.37% and 1.81% respectively (Fig. 6).

4. Conclusions

The usefulness of a given method for determining reference values results from the uncertainty inherent in the method with regard to the permissible error values of the calibrated WIM system. It is generally understood that an adequate accuracy class for WIM systems implemented for the direct enforcement of existing regulations is the Class A(5). The Class B+(7) is also considered. Permissible errors values for this accuracy classes are presented in Table 6 [13] in connection with accuracy of the reference method *i.e.* the LS-WIM system.

By comparing the permissible error values with the maximum error values determined using the low-speed WIM scale (LS-WIM), it can be seen that reference values determined in this manner may be successfully used in the process of calibrating the both class of WIM systems, without the need to use a platform scale.

Table 6. Boundary errors of a B+(7) and an A(5)-class WIM systems.

Type of measured value	Permissible error of Class B+(7) [%]	Permissible error of Class A(5) [%]	Maximum error of reference value – LS [%]
Gross vehicle weight	7	5	1.15
Multiple axle (axle group)	10	7	1.81
Single axle	11	8	2.60
Component axle of an axle group	14	10	2.60

This is a significant conclusion as it indicates that a considerable simplification and increase in the efficiency of the procedure of determining reference values can be achieved, thus increasing the effectiveness (in terms of logistics and costs) of the entire WIM system calibration process.

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