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Experimental assessment of the accuracy of High Speed Weigh-In-Motion systems

Ryszard Sroka, Janusz Gajda, Piotr Burnos, Mateusz Danioł
AGH University of Krakow
Anna Kania-Markocka, Wiktor Ślusarski, Robert Ziółkowski, Piotr Strzałka
Central Office of Measures, Warsaw

Corresponding author's e-mail address: rysieks@agh.edu.pl (Ryszard Sroka)

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Abstract

This paper presents the results of research on the accuracy of two HS-WIM systems located in Wielka Wieś near Tarnów, Poland. Each of the systems is fitted with eight load sensors laid out in four lines, manufactured using different technologies. Quartz and bending plate sensors were used. The study of the accuracy of these systems was conducted using the pre-weighed vehicles method, after two years of operation of the systems, without correction of calibration factors during this period. The results obtained indicate that in both systems there is an systematic error with a value of approximately 2.9 %. These results have made it possible to assess the current error of the HS-WIM systems and to assign to them accuracy classes according to COST 323 guidelines. The calibration which was performed on both systems allowed for the elimination of among others of systematic error and showed the possibilities for reducing random errors in the analysed systems. Studies such as this one may be useful for assessing the periods between successive calibrations of HS-WIM systems in order to maintain accuracy in the assumed class in accordance with COST 323 (e.g. A(5), B+(7), B (10) etc.).

1. Introduction

High Speed Weigh-In-Motion systems(HS-WIM) are a specific type of measurement system [1], which are assign to different accuracy classes according to COST 323 guidelines [2]. Their specific nature results from the fact that load sensors are installed in a road pavement. In effect, this fragment of pavement becomes an element of the measurement system which has a significant impact on its metrological properties. The weighing result of the vehicle is dependent on many factors, among which are: environmental factors (first of all temperature), factors associated with the vehicle (the number and configuration of axles, the speed and manner in which the vehicle crosses the weighing station, the type and current state of the vehicle suspension), and factors associated with the HS-WIM system itself (the number of load sensors and the technology in which they were manufactured, the frequency of calibration, the quality and type of pavement in which the sensors are installed). Attempts are made to limit the influence of the mentioned factors on the weighing result. In [3] the idea of compensating the influence of temperature on piezoelectric load sensors was presented. The weighting results were corrected using the polynomial regression method and the Genetic Algorithm Back Propagation (GA-BP) neural network. The use of a neural network allowed for a 100-fold reduction in the temperature coefficient value. Paper [4] presents research results on the influence of air temperature and speed of the weighed vehicle on weighing errors in WIM systems equipped with various load sensors, i.e. quartz, polymer, and ceramic piezoelectric sensors. Quartz sensors showed no sensitivity to speeds above 30 km/h. Polymer and ceramic piezoelectric sensors showed sensitivity to temperature and speed. On this basis, an auto-compensation algorithm was proposed, especially for ceramic sensors.

However, the aim of the research presented in this paper is not to assess the sensitivity of WIM systems to the above-mentioned factors. This problem is already well documented in the literature. Our goal is to evaluate changes in the accuracy of WIM systems over a longer period of their operation, approximately 2 years, as well as a comparison in this respect of two WIM systems equipped with load sensors made using different technologies. There are no reports in the literature regarding this issue. Finding the answer to the question regarding changes in the metrological properties of WIM systems as a function of time is important from the point of view of developing recommendations regarding the periods of their metrological re-verification. Attention was drawn to the need to assess long-term WIM system performance in [5]. This paper proposes the use of axle load spectra attributes to assess temporal changes of consistency of measurement data from the WIM system.

Study of the metrological properties of an HS-WIM system, including accuracy, is difficult due to the absence of metrological standards of axle load, and the impossibility of conducting static calibration (in the case of most types of load sensors used), as well as the impossibility of controlling the intensity of environmental factors which impact the weighing result. Constant monitoring of the accuracy of HS-WIM systems is, however, necessary, in particular in the case of their use in direct mass enforcement systems. The idea of using WIM systems for mass enforcement was described in [6]. Such use of WIM systems in Belgium became possible thanks to the development by Walloon Public Service of the structure of such WIM systems and the procedure for their metrological approval. The paper [7] presents experiences related to the implementation of the National Dynamic Axle Weight Measurement System in Hungary. The system integrates 100 control points located on the road network. The paper [8] contains an assessment of the level of development of WIM systems in Europe, and in particular their use for direct mass enforcement. The prospects for standardization of WIM systems in Europe were also presented. In [9] a summary of a large project coordinated by the French Ministry of Ecology, Sustainable Development and Sea was presented. The aim of the project was to demonstrate the possibility of using WIM systems for direct enforcement of overloaded vehicles. The aim is, on the one hand, to modify the applicable legal regulations to enable the use of such systems, and, on the other hand, to achieve the necessary weighing accuracy, which is estimated at ±5 % for the gross vehicle weight, and ±10 % for axle loads. In [10] a method for assessing the reliability of measurement data obtained from WIM systems is presented. The proposed method is based on two groups of parameters. The first one contains the results of measuring the intensity of meteorological parameters. The second one contains parameters characterizing the trajectory of the vehicle passing through the WIM station. The impact of the trajectory of the vehicle weighed on the WIM station on the accuracy of weighing results is discussed in the paper [11]. The subject of the research was also the influence of vehicle dynamics, i.e. acceleration/braking. A change in the amplitude and value of the signal registered by the load sensors was found as a function of the position of the contact between the sensor and the tire.

The use of WIM systems for direct mass enforcement makes it necessary to search for new experimental methods for the assessment of the accuracy of such systems. One possible solution is the application of the auto-calibration procedure described in details in [12, 13]. This method undoubtedly has many advantages, however the main disadvantage is the high uncertainty of the static axle load value of the characteristic vehicle which in this procedure is assumed as the reference value and the lack of metrological traceability in this method.

Regardless of the tests and studies conducted, the basic method allowing for the assessment of HS-WIM systems remains the pre-weighed vehicle method. This involves multiple runs across the weighing station by vehicles which have been previously weighed on a non-automatic scale, further referred to as a weighbridge. The gross vehicle weight (GVW) indicated in this way is taken as the reference value and used for comparison with the results of dynamic weighing. The reference value of loads of specific axles of the vehicles is established proportionally to the gross weight based on measurements made on a vehicle scale for weighing vehicles in motion, further referred to as an LS-WIM scale. Both the weighbridge and the LS-WIM scale are subject to legal metrological control.

This paper presents the results of research on the accuracy of two experimental HS-WIM systems conducted using precisely this method. The structure of both HS-WIM systems is described in detail in [14]. The results obtained indicate that after two years of operation, there is an systematic error with a value of approximately 2.6 % - 2.9 %.

Measurement data gathered during the conducted experiment were used to re-calibration the studied HS-WIM systems. Two different calibration algorithms were used. The result was the near-complete elimination of systematic error from the weighing results of the vehicles. This thus allowed for the determination of the remaining random errors of the studied systems.

Work is ongoing at the Mass Laboratory of the Polish Central Office of Measures aiming at bringing HS-WIM systems under metrological control in terms of type approval, initial verification, and subsequent periodic verification. In this scope, a set of metrological regulations is being designed which are intended to establish and regulate the principles of verification of the metrological properties of these systems. Upon approval of type and verification, the subject of checking would be mainly measurement errors involving selected parameters of vehicles, such as axle load, axle group load, and gross vehicle weight. For this reason, the studies at Wielka Wieś were conducted with an eye to the practical verification of the possibility of implementing the regulations being designed and satisfying metrological requirements.

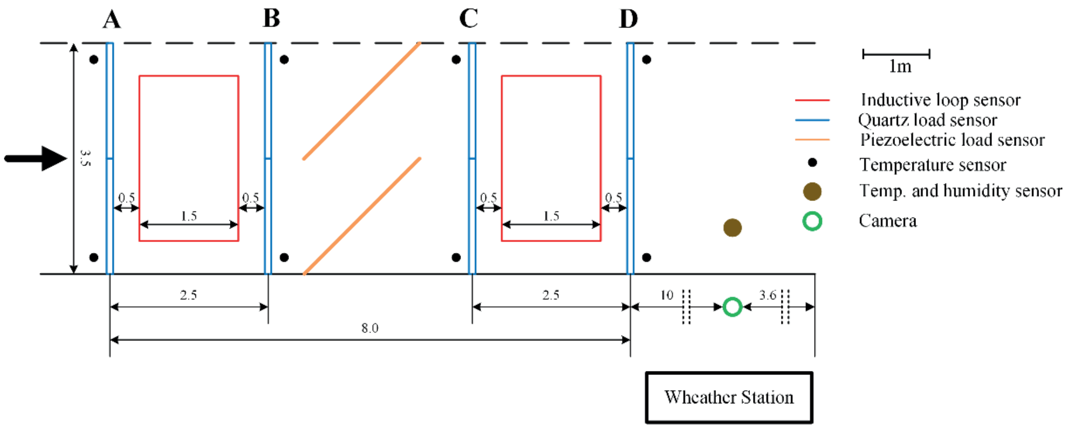
The paper is organised in the following way: in section II there is a description of the way in which the two studied HS-WIM systems were constructed, using different technologies. Next, experiments were conducted and in section III there is a discussion of the measurement data gathered. In section IV, the manner in which the measurement results were processed is described. Section V contains the results of the assessment of accuracy of both HS-WIM systems, both with reference to the gross weight of the vehicles and to the static load of individual axles and groups of axles. Section VI contains a discussion of the results of the calibration implemented and of the impact of this procedure on the errors in the results obtained from the studied HS-WIM systems.

2. Description of the HS-WIM station

The aim of this study was the assessment of the accuracy of an experimental HS-WIM (High Speed Weigh in Motion) station comprising two HS-WIM systems. At the first station, a set of eight Kistler quartz load sensors was installed in four line perpendicular to the direction of motion of the vehicles. At the second system, a set of eight PAT bending plate sensors was installed, also in four lines, each 3.5 m long. Both stations are installed in one lane of the road, and the distance between the load sensors at each end of the system is 15 m. The placement of the sensors along the station allows for the load of each wheel of the vehicle to be measured four times. Induction loops and piezoelectric sensors were installed between the load sensors in order to monitor the trajectory of the weighed vehicle. Additionally, the test station was equipped with sensors which measure the temperature of the pavement, the wind direction and strength, the presence of precipitation and/or moisture on the road surface, the presence of a layer of water on the road surface, and salt levels on the road surface. Cameras installed at the stations allow for the correct passage of the vehicle across the weighing station to be monitored and for registration the plate numbers to be recognised.

At a distance of about 500 m from the HS-WIM station there is a low-speed weigh-in-motion (LS-WIM)

(a)



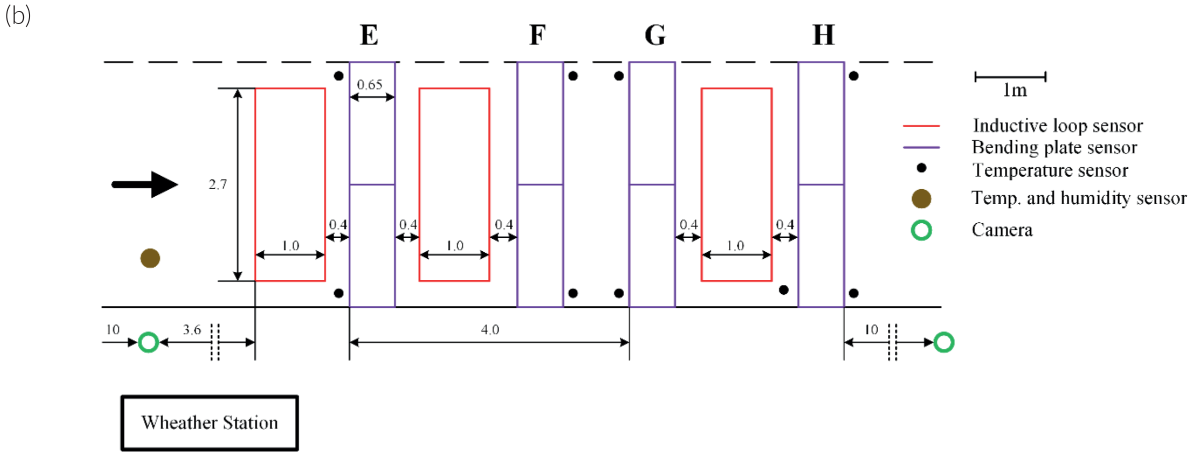


Fig. 1. Structure diagram of the designed WIM station: (a) the section with quartz sensors; (b) the section with bending plate sensors. A, B, C, D, E, F, G, H – successive lines of sensors.

system. The HS-WIM system structure is presented in Fig. 1.

The studies described in this paper were conducted two years after the installation of the load sensors and the initial calibration of the systems.

3. Description of the experiment

The pre-weighed vehicles method was used for the assessment of accuracy and the performance of calibration of both HS-WIM systems. This method involves multiple runs across the studied station by test vehicles which have previously been weighed on a non-automatic static vehicle scale and on a low-speed dynamic weigh-in-motion scale. The results of the measurements obtained on the non-automatic vehicle scale allow for the determination of the correct gross vehicle weight (GVW) of the vehicles while the results from the LS-WIM scale allow for the determination of the static load of particular axles. The flow chart illustrating the sequence of carried out experiments is presented in Fig. 2.

The parameters of these scales are presented in the Table 1.

The non-automatic vehicle scale used in this case had an accuracy class of III, while the LS-WIM scale was D2 [15]. In the experiments conducted in this study, three lorries were used, respectively: a two-axle rigid body vehicle, a three-axle vehicle, and a five-axle vehicle (a two-axle road tractor with a three-axle semi-trailer). The reference value for the gross vehicle weight(GVW) of each vehicle was assumed as the result of weighing on the non-automatic vehicle scale. The reference values for single axle static loads and axle group loads in all the vehicles were determined on the LS-WIM scale. A correction algorithm for axle weighing results was applied and the determination of reference values for the static

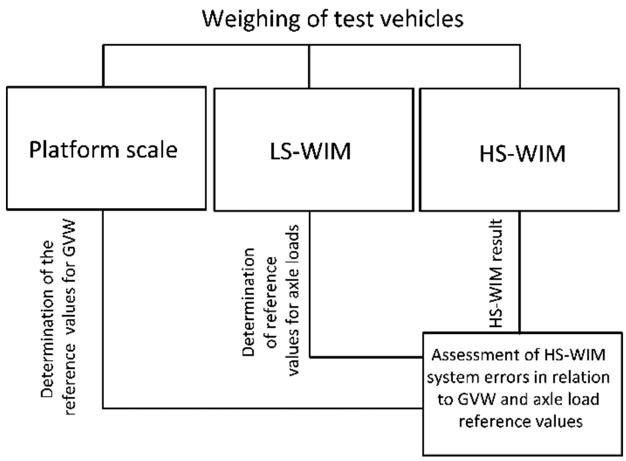


Fig. 2. Flow chart illustrating the sequence of carried out experiments.

Table 1. 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	Platform scale	WITWAG	III	400 - 60000	20	N/A
2	Low-speed LS-WIM scale, type VM 1.2	TENZOVAHY – The Czech Republic	D2	400 - 20000	20	1 - 6

load of individual axles is described in the next section.

Each test vehicle passed over both systems 15 times at speeds of approximately 50km/h, 60km/h and 80km/h, completing five runs at each of the speeds. In total, 45 weighing results were obtained for the vehicles per station, at various speed values. Considering that each HS-WIM system is equipped with four lines of sensors, this means that a total of 180 results was obtained for each HS-WIM system, at varying speeds.

Figure 3 illustrates the measurement error for gross vehicle weight (GVW) normalised for the reference values of the test vehicles, determined on the basis of measurement results obtained from a single quartz sensor (Fig. 3a). The average value of error was 2.6 %. Removing the average from the entire population of errors resulted in a maximum GVW measurement error not exceeding 6 % (Fig. 3b). This conclusion is confirmed by the distributions illustrated in Figure 4. It should be clearly stated that these are results concerning a single load sensor. The installation of four load sensors allows for a further reduction of error, for example by using the simple averaging of results from successive sensors method.

Analogous characteristics of the HS-WIM system fitted with bending plate sensors are presented in Figures 5 and 6. The number of correct test runs in this case amounted to 160. The average value of GVW measurement error in the case of these sensors was 2.9 %. After correction, the relative GVW measurement error on a single bending plate load sensor, in the extreme case, was 10 %. Histograms illustrating the distribution of relative errors are shown in Figure 6.

4. Processing of measurement results

The result of weighing on the non-automatic scale (for every test vehicle) was assumed as the reference value for the gross vehicle weight (GVW). As the reference value for axle group load and single axle load, the corrected average value of five measurements (weighing only in one direction of passage of the test vehicle) of axle load on the LS-WIM scale at Wielka Wieś was assumed. The errors of both HS-WIM systems were defined with reference to these reference values.

The reference values of axle group load and single axle load were determined according to the following algorithm, described in [15]. The algorithm comprises the following steps:

1. On the basis of each weighing result obtained from the LS-WIM scale, in accordance with dependency (1), the axle load of a multiple axle (if such an axle appears in the weighed vehicle) was determined.

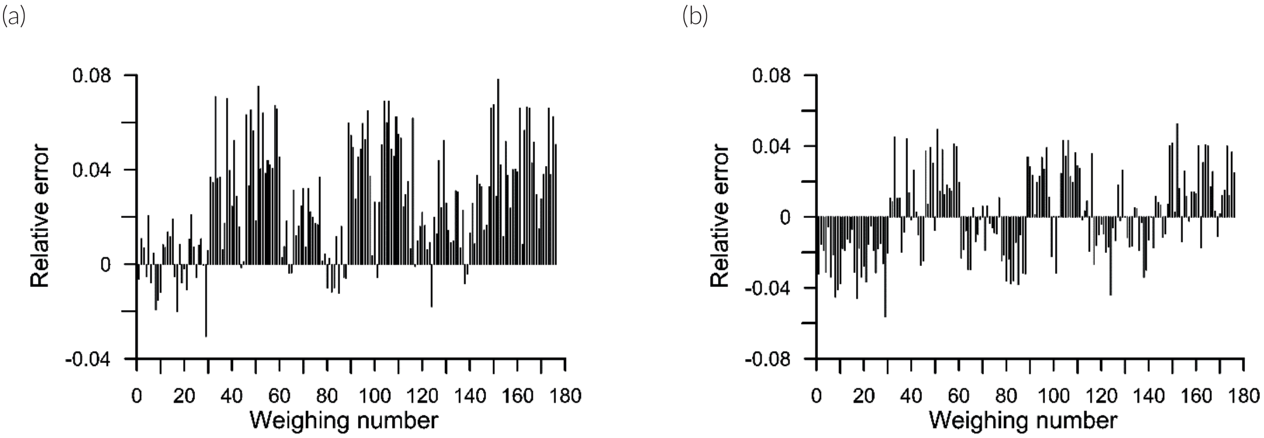


Fig. 3. Relative GVW measurement error on a single load sensor, at the HS-WIM system fitted with quartz sensors. (a) – error without correction; (b) – error corrected by removing the average value.

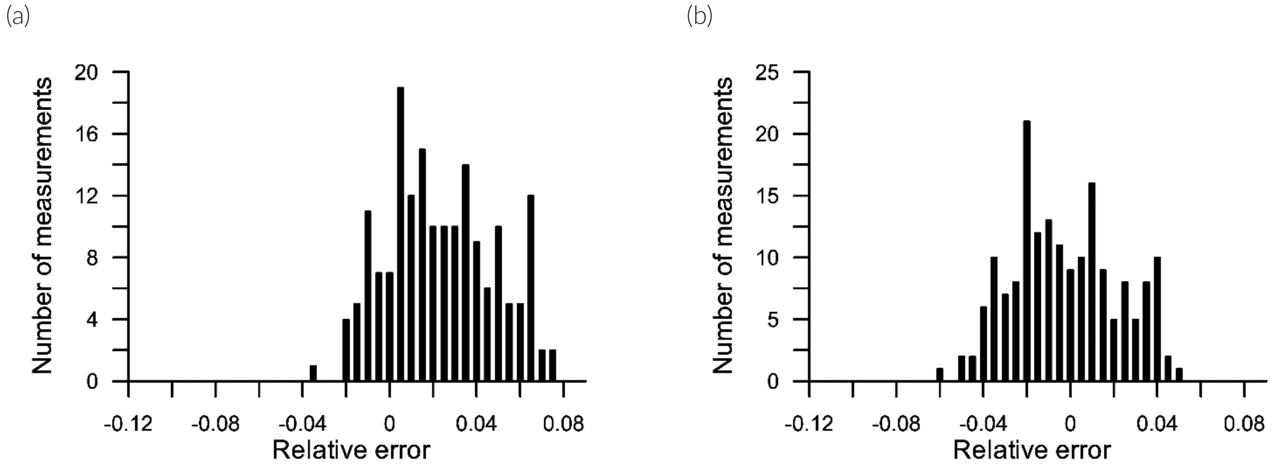


Fig. 4. Histograms of GVW measurement error on a single load sensor, at the HS-WIM system fitted with quartz sensors. (a) – error without correction; (b) – error corrected by removing the average value.

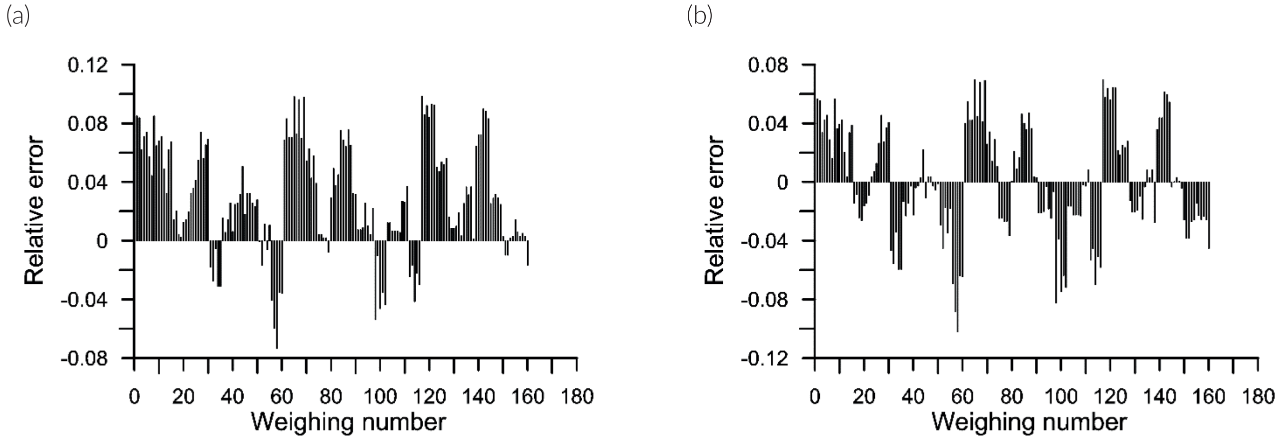


Fig. 5. Relative GVW measurement error on a single load sensor, at the HS-WIM system fitted with bending plate sensors. (a) – error without correction; (b) – error corrected by removing the average value.

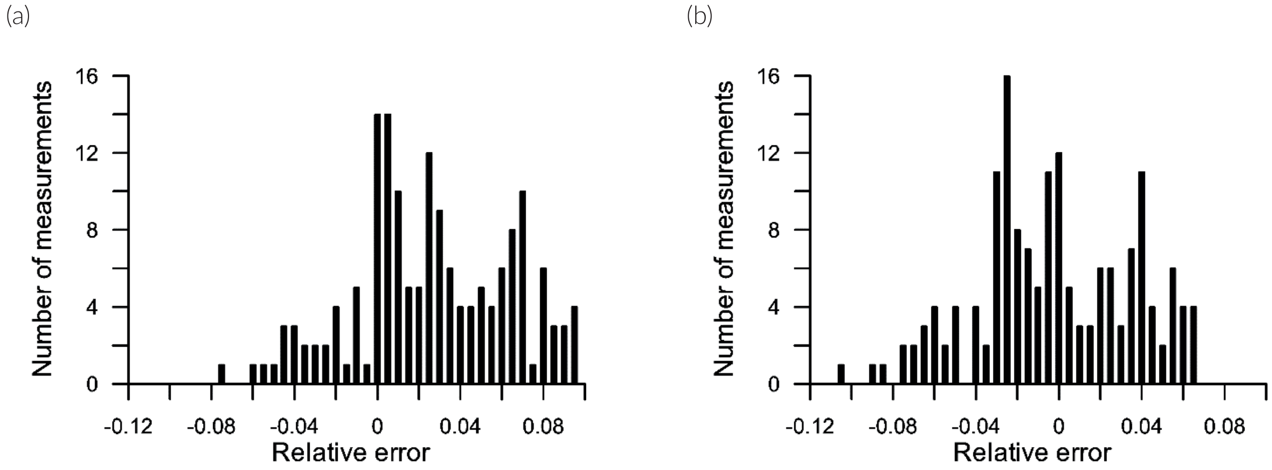


Fig. 6. Histograms of GVW measurement error on a single load sensor, at the HS-WIM system fitted with bending plate sensors. (a) – error without correction; (b) – error corrected by removing the average value.

$$Group\_LS_{k,i} = \sum_{j=1}^{r} Axle\_LS_{j,k,i} \tag{1}$$

where:

$Axle\_LS_{j,k,i}$– is the weighing result of the j-th of the component axle of the i-th axle group, obtained in the k-th experiment on the LS-WIM,

j – number of the component axle, j=1, 2, …r,

i – number of the axle group,

k – weighing number,

r – number of component axles comprising the i-th axle group.

2. On this basis, in accordance with dependency (2) the average load value of the i-th axle group was determined.

$$\overline{Group}\_LS_i = \frac{\sum_{k=1}^{nLS} Group\_LS_{k,i}}{nLS} \tag{2}$$

where:

i – number of the axle group,

nLS – total number of weighings of a given vehicle on the LS-WIM scale.

3. Similarly, in accordance with dependency (3), the average load value of each individual axle in a given vehicle was determined.

$$\overline{Axle}\_LS_l = \frac{\sum_{k=1}^{nLS} Axle\_LS_{k,l}}{nLS} \tag{3}$$

where:

l – number of the individual axle,

$Axle\_LS_{k,l}$ – k-th weighing result of the l-th axle on the LS-WIM scale.

4. The average value of the total vehicle weight of the test vehicle was determined as the sum of the averages of load values for all axles and axle groups appearing in the test vehicle (4).

$$\overline{VM} = \sum_{l=1}^{s} \overline{Axle}\_LS_l + \sum_{i=1}^{g} \overline{Group}\_LS_i \tag{4}$$

where:

s – number of individual axles in the test vehicle,

g – number of axle groups in the test vehicle.

The concept for determining the reference axle load values of test vehicles is based on the assumption that the total weight of the test vehicle should be equal to the result of the measurement of the gross vehicle weight of the test vehicle(GVW) obtained on the weighbridge.

5. The reference load value of the i-th axle group was determined in accordance with dependency (5).

$$\overline{Group\_ref_i} = \overline{Group}\_LS_i \times \frac{GVW}{\overline{VM}} \tag{5}$$

6. The reference load value of the l-th single axle was determined in accordance with dependency (6).

$$\overline{Axle}\_ref_l = \overline{Axle}\_LS_l \times \frac{GVW}{\overline{VM}} \tag{6}$$

The reference axle load values of the three test vehicles determined in this way are presented in Table 2. The standard deviation values (std) contained in the table define the random variability of weighing results of individual axles on the LS-WIM scale.

5. Assessment of the measurement accuracy of axle load and GVW at the HS-WIM systems

The weighing accuracy of vehicles at both HS-WIM systems was assessed separately with regard to the accuracy of measurement of the gross vehicle weight (GVW) of the test vehicles as well as to the accuracy of the measurement of the single and group axle static load. Both the gross weight and the static load were determined based on the averaging of weighing results obtained from each of the four load sensors which both HS-WIM systems are fitted with.

Figure 7 shows histograms of the relative error of the measurement of the gross weight of the test vehicles for

Table 2. Weighing results of test vehicles on the weigh bridge (GVW) and on the LS-WIM scale

	GVW [kg]	Axle load I			Axle load II			Multiple axle load		
		Average value [kg]	Ref. value [kg]	Std [kg]	Average value [kg]	Average value [kg]	std [kg]	Average value [kg]	Average value [kg]	std [kg]
2-axle vehicle	16240	6296	6298	26.1	9940	9942	24.5	x	x	x
3-axle vehicle	25380	7268	7268	22.8	x	x	x	18112	18112	54.0
5-axle vehicle	39860	7160	7184	14.1	11308	11346	10.9	21260	21331	31.6

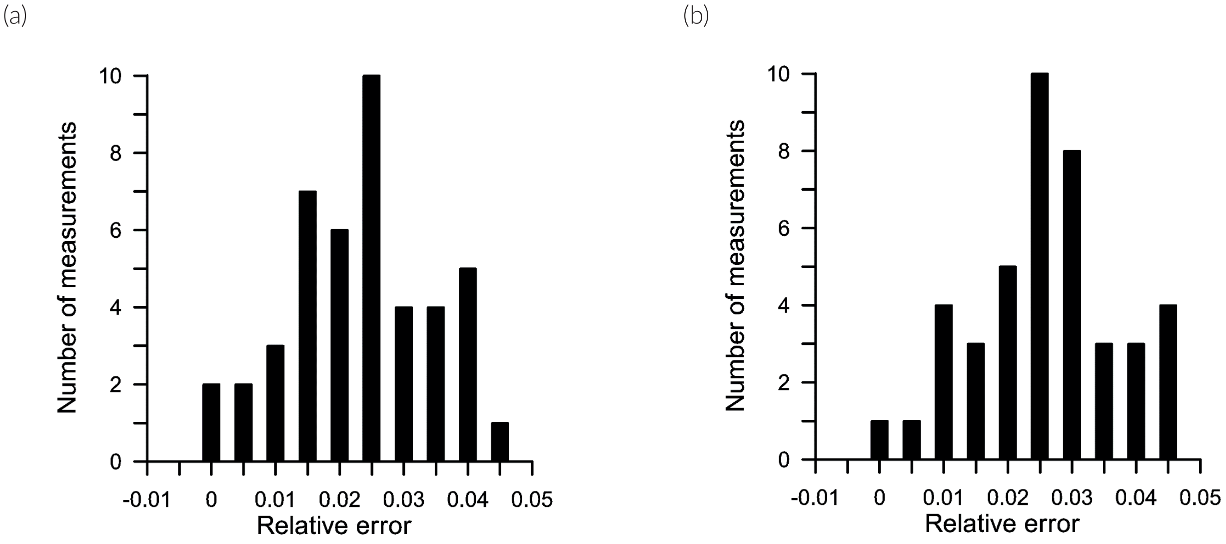


Fig. 7. Histograms of the relative error of GVW measurement at four-sensor HS-WIM systems. a) HS-WIM system fitted with quartz load sensors, b) HS-WIM system fitted with bending plate load sensors.

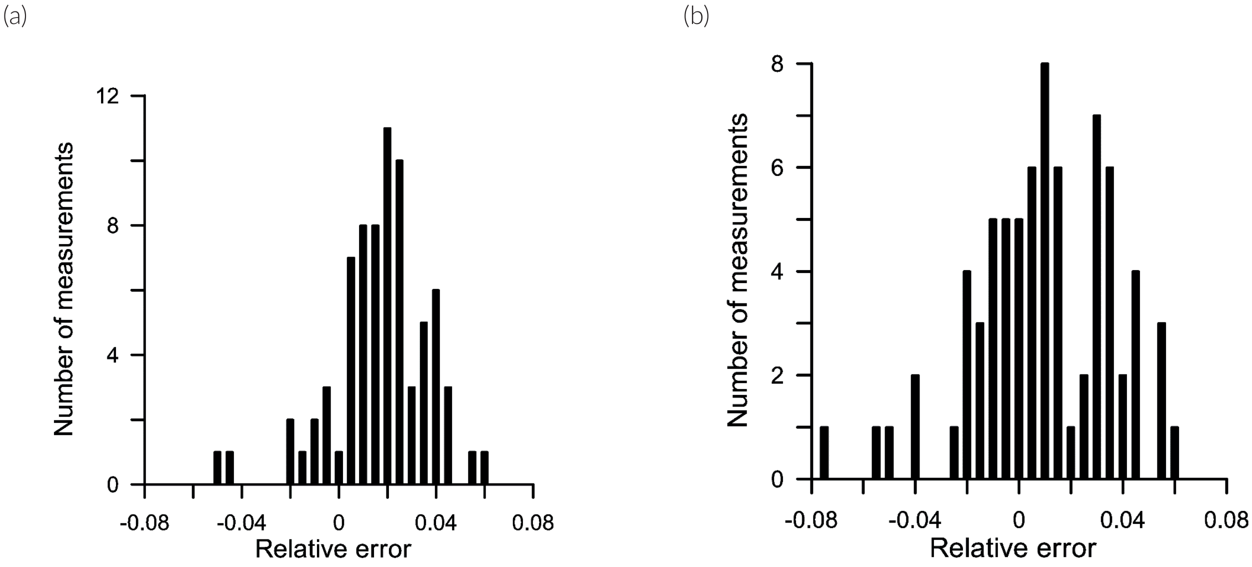


Fig. 8. Histograms of the relative error of measurement of single axle static load at four-sensor HS-WIM systems. a) HS-WIM system fitted with quartz load sensors, b) HS-WIM system fitted with bending plate load sensors.

the HS-WIM system fitted with quartz load sensors (Fig. 7a) and bending plate load sensors (Fig. 7b) respectively. The maximum GVW error in both cases does not exceed 4.5 %. Both histograms are asymmetrical, which can be corrected by subsequent calibration of both systems. Such calibration will cause an improvement in the accuracy of weighing. The issue of calibration of the systems is discussed in the following section.

Measurement errors of single axle load were determined with regard to the assumed reference values presented in Table 2. For each of the studied HS-WIM systems, the measurement result was accepted as the average value of the results obtained from each of the four load sensors. Single axles appeared in all of the test vehicles. In total during the course of the experiment, 74 weighings of single axles were performed. Histograms of errors are shown in Fig. 8. The maximum errors of measurement of static load of a single axle at the HS-WIM system fitted with quartz load sensors were within the range of [–5 % - +6 %]. For the HS-WIM system fitted with bending plate sensors, this range was [–7.1 % - +6 %].

Weighing errors of axle groups (two joined axles) in the three-axle vehicle (the weighing result was accepted as the average value from four load sensors) at the HS-WIM system fitted with quartz load sensors were within the range [+0.3 % + 3.8 %], while for the HS-WIM system

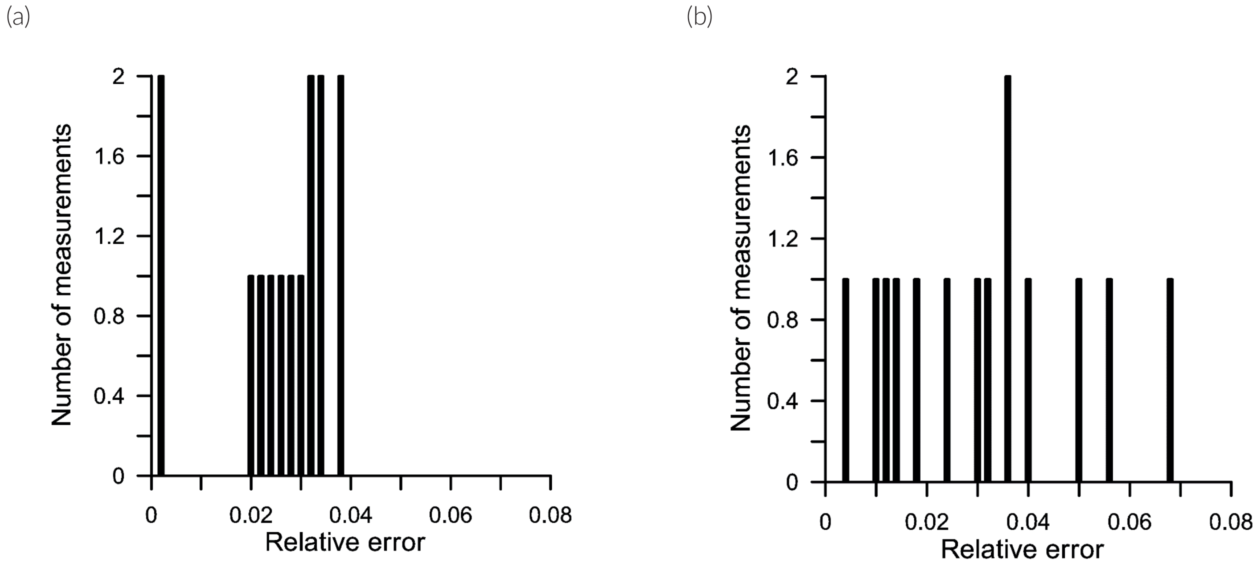


Fig. 9. Histograms of the relative error of measurement of axle group static load (double axle) at four-sensor HS-WIM systems. a) HS-WIM system fitted with quartz load sensors, b) HS-WIM system fitted with bending plate load sensors.

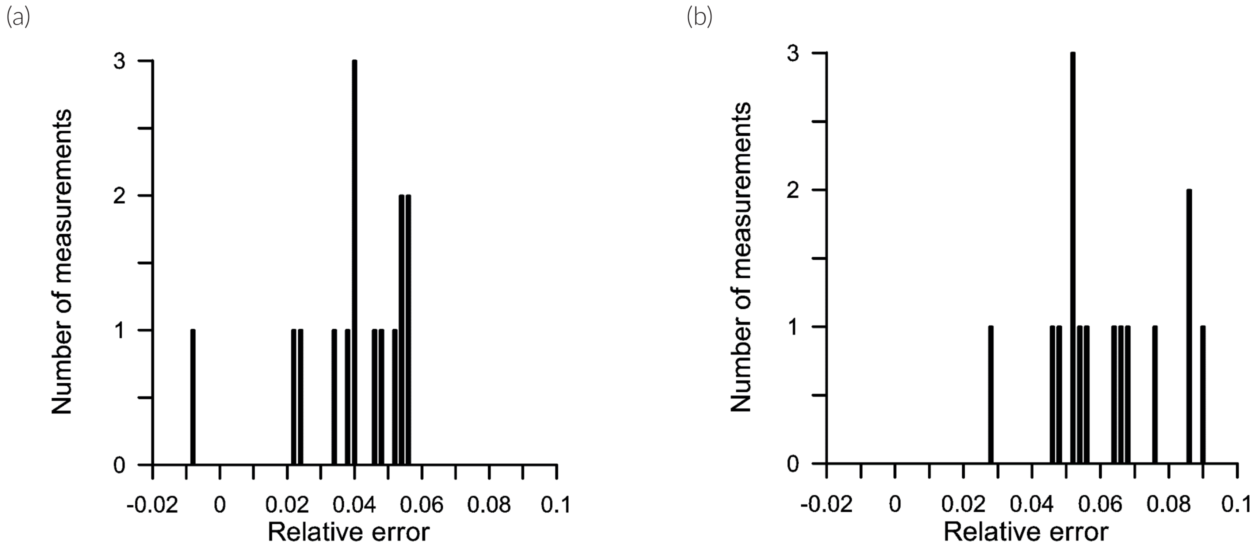


Fig. 10. Histograms of the relative error of measurement of axle group static load (triple axle) at four-sensor HS-WIM systems. a) HS-WIM system fitted with quartz load sensors, b) HS-WIM system fitted with bending plate load sensors.

Table 3. Comparison of errors in HS-WIM system fitted with bending plate load sensors against permissible error values for systems of accuracy class B+(7) [2]

Type of quantity measured	Permissible error %	Maximum error of the HS-WIM system [%]		
		2-axle vehicle	3-axle vehicle	5-axle vehicle
Total gross weight	7	4.5	4.5	4.5
Axle group	10	---	6,8	9,0
Single axle	11	7.1	7.1	7.1
Component axle of axle group	14	---	7.7	9.4

Table 4. Comparison of errors in HS-WIM system fitted with ᵍuartz load sensors against permissible error values for systems of accuracy class B+(7) [2]

Type of quantity measured	Permissible error %	Maximum error of the HS-WIM system [%]		
		2-axle vehicle	3-axle vehicle	5-axle vehicle
Total gross weight	7	4.5	4.5	4.5
Axle group	10	--	3.8	5.7
Single axle	11	6.0	6.0	6.0
Component axle of axle group	14	---	4.8	6.5

fitted with bending plate sensors this range was [+0.5 % - +6.8 %] (Fig. 9).

Weighing errors of axle groups (three joined axles) in the five-axle vehicle at the HS-WIM system fitted with quartz load sensors were within the range [–0.8 % - +5.7 %], while for the HS-WIM system fitted with bending plate sensors this range was [+2.5 % - +9.0 %] (Fig. 10).

In Tables 3 and 4, the maximum values of relative errors determined during the study of both HS-WIM systems are presented. The error values determined are compared with the permissible errors defined for systems of accuracy class B+(7) in [2]. This comparison unambiguously indicates that both studied HS-WIM systems fulfil the requirements defined for systems of accuracy class B(+7).

6. Calibration of the HS-WIM systems

The ideal static characteristics for an HS-WIM system describing the dependency between the actual gross weight of the measured vehicle (GVW) and the weighing result can be defined by the equation

result = 1·*GVW*. In reality, influenced by a variety of factors, the static characteristics differ from the ideal characteristics, leading to errors of weighing of a systematic nature. The course of the actual characteristics can be determined experimentally using the pre-weighed vehicles method. The process of the calibration of the HS-WIM system is thus aimed at correcting its characteristics towards a more ideal form. It must be stressed here that achieving an ideal outcome is in practical terms impossible. This is due to random errors contained in the weighing results of the test vehicles, a limited number of experiments and the number of vehicles used in them, the limited range a variability of weights of test vehicles, as well as the non-linear static characteristics of the calibrated HS-WIM systems.

Figure 11 shows the weighing results of test vehicles and the static characteristics of both studied HS-WIM systems. The actual static characteristics were determined with approximation of experimental results on a linear model whose coefficient was calculated using the least squares method. The actual, linear characteristics of the HS-WIM system fitted with quartz load sensors thus determined are described by the equation *result* = 1.037·*GVW*-258.8 kg. The analogously determined static characteristics of the HS-WIM system fitted with bending plate load sensors are described by the equation *result* = 1.043·*GVW*-340.0 kg.

The aim of the calibration of the HS-WIM system is the experimental determination of the coefficients of the algorithm describing the method for processing the measurement results obtained directly from the HS-WIM system in order to determine the gross weight of the weighed vehicle (GVW) or the load of its axles. In the general case, this algorithm takes the form (7).

$$D_{k,v} = \frac{1}{C} \cdot W_{k,v} + b \tag{7}$$

where:

C and b – coefficients of the algorithm searched for in the calibration process,

$W_{k,v}$ – weighing result of the v-th test vehicle (GVW or axle load) obtained in the k-th run across the station,

$D_{k,v}$ –weighing result of the v-th test vehicle (GVW or axle load) after calibration obtained in the k-th run across the station,

v – number of the test vehicle,

k – run number of the test vehicle, weighing number.

In practice, for simplification the equation $b = 0$ is often assumed. This assumption is in fact necessary when only one calibrating vehicle is used.

In the paper [16] the properties of four different algorithms for determining the values of the coefficients C and b were presented. For this paper, the authors used two algorithms of the form (8) and (9) respectively. Both algorithms ensure minimisation of the mean squared error of the weighing result. Algorithm (8) minimises the mean squared error for the particular case $b = 0$, while algorithm (9) does so for the general case $b \neq 0$

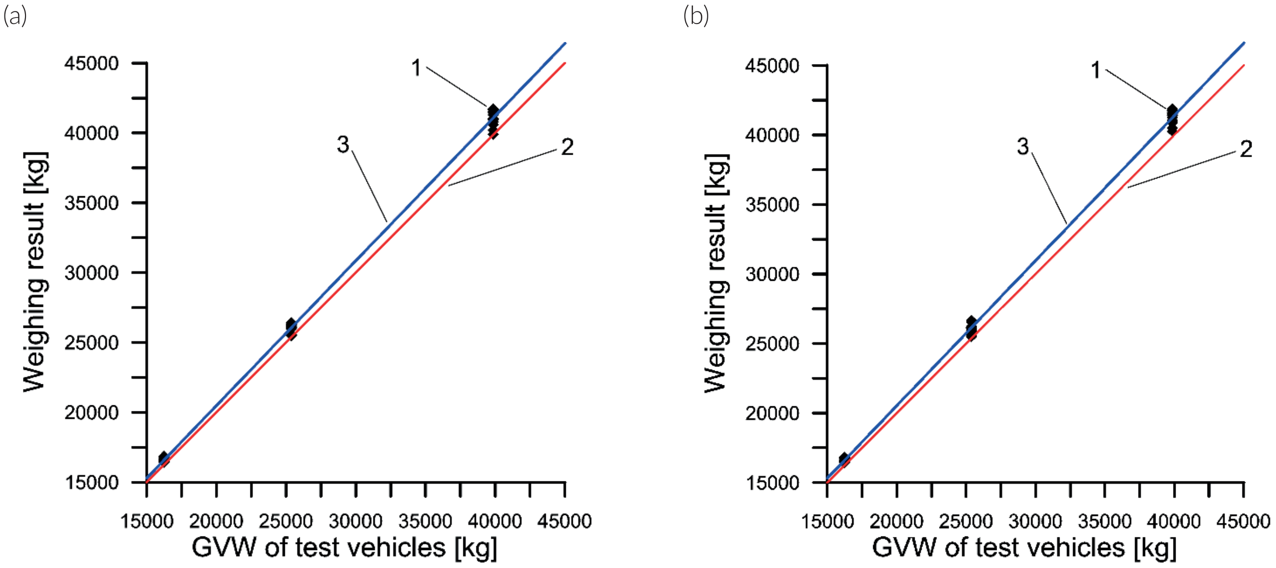


Fig. 11. Static characteristics of the studied HS-WIM systems: a) – characteristics of the HS-WIM station fitted with quartz load sensors, b) – characteristics of the HS-WIM system fitted with bending plate load sensors, 1 – weighing results for the three test vehicles, 2 – ideal static characteristics, 3 – actual static characteristics.

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$$C_1 = \frac{\sum_{v=1}^{vs} n_v\cdot(M_v)^2}{\sum_{v=1}^{vs}(M_v \sum_{i=1}^{nv} D_{k,v})} \qquad b_1 = 0 \tag{8}$$

$$C_2 = \frac{(\sum_{v=1}^{vs} n_v)(\sum_{v=1}^{vs} n_v\cdot(M_v)^2)-(\sum_{v=1}^{vs} n_v\cdot M_v)^2}{(\sum_{v=1}^{vs} n_v)(\sum_{v=1}^{vs}\sum_{k=1}^{nv} M_v\cdot D_{k,v})-(\sum_{v=1}^{vs} n_v\cdot M_v)(\sum_{v=1}^{vs}\sum_{k=1}^{nv} D_{k,v})} \tag{9a}$$

$$b_2 = \frac{(\sum_{v=1}^{vs} n_v\cdot(M_v)^2)(\sum_{v=1}^{vs}\sum_{k=1}^{nv} D_{k,v})-(\sum_{v=1}^{vs} n_v\cdot M_v)(\sum_{v=1}^{vs}\sum_{k=1}^{nv} M_v\cdot D_{k,v})}{(\sum_{v=1}^{vs} n_v)(\sum_{v=1}^{vs} n_v\cdot(M_v)^2)-(\sum_{v=1}^{vs} n_v\cdot M_v)^2} \tag{9b}$$

where:

η_v for v = 1, 2, ….vs, – number of runs of thev-th test vehicle,

M_v – reference value of the weight of the v-th test vehicle or the static load of a selected axle (Table 2),

vs – number of test vehicles used in the calibration process.

The calibration coefficients (8) and (9) were determined for both HS-WIM systems based on the gross vehicle weight (GVW) values of all three test vehicles, determined on the weighbridge. The determined calibration coefficients are presented in Table 5.

The effectiveness of the calibration process can be assessed based on the discrepancies between the ideal static characteristics and the actual characteristics of each HS-WIM system determined before and after calibration. The discrepancy between characteristics was determined as the RMS error (Table 5).

This effectiveness can also be assessed by comparing the histograms of weighing error determined before (Fig. 7) and after calibration (Fig. 12).

As it can be seen from the histograms presented, after calibration of both HS-WIM systems, the maximum error does not exceed 3.0 %. It should be stressed here that the weighing result was determined as the mathematical average of the results of weighing on four load sensors, thus reducing the random error component. It should also be pointed out that the weighing results determined with such a maximum error are not numerous, and assessment of accuracy based on the maximum error generally leads to pessimistic conclusions. In reality however, the set of results is dominated by results where the error is within the range [-1.0 % - +1.0 %]. Therefore, a more valid assessment of the HS-WIM system can be obtained by assessing its reliability characteristic. A discussion of this method is beyond the scope of this paper. Details on this method can be found in the papers [17-19].

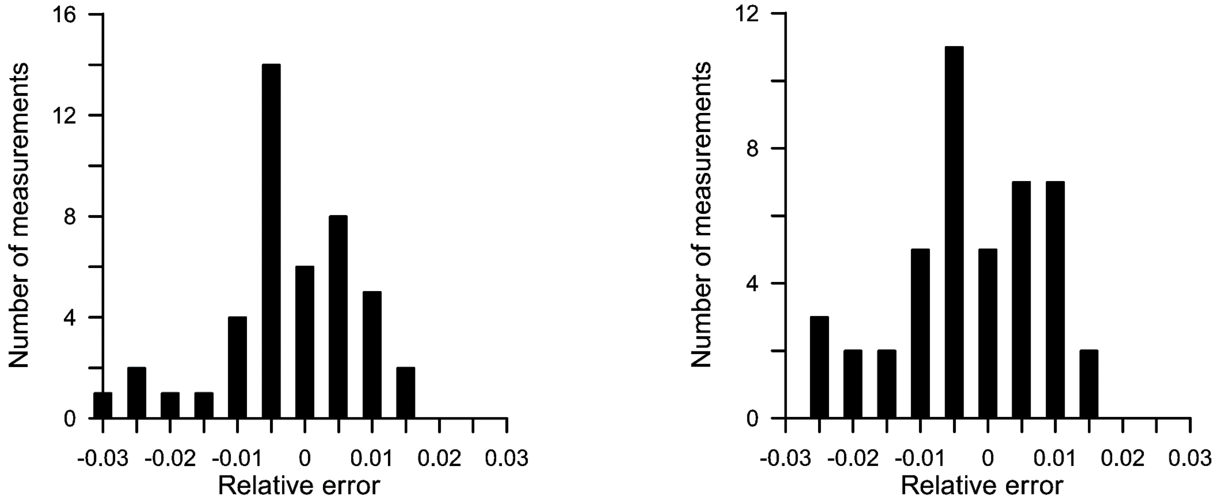

Fig. 12. Histograms of the relative error of GVW measurement at four-sensor HS-WIM systems determined after calibration using algorithm (9). a) HS-WIM system fitted with quartz load sensors, b) HS-WIM system fitted with bending plate load sensors.

Table 5. Values of calibration coefficients determined for the studied HS-WIM systems and the mean squared error between ideal static characteristics of the HS-WIM systems before and after calibration using algorithms (8) and (9)

WIM system	RMS error before calibration [%]	C_1	RMS error after calibration using (8) [%]	C_2	b_2 [kg]	RMS error after calibration using (9) [%]
Quartz sensors	2.91	0.9723	0.24	0.9645	-258.8	4.5 x 10^{-3}
Bending plate sensors	3.13	0.9687	0.31	0.9584	-340.0	4.3 x 10^{-3}

7. Summary

Assessment of the accuracy of two four-line HS-WIM systems constructed using different technologies conducted after two years of operation of the systems has delivered quite optimistic results. Based on the results of the experiments performed, the following conclusions can be drawn:

- changing the slope of the static characteristic, which occurred during the two-year period of operation of the WIM systems, caused a systematic error of 2.6 % - 2.9 %.
- in the case of both tested WIM systems, a similar shift in the zero of the static characteristics was observed, amounting to approximately 300 kg.
- the distributions of weighing errors occurring in both WIM systems are asymmetric towards zero. This means that it is possible to reduce them by recalibrating the systems.
- the calibration performed allowed for the virtually complete elimination of the systematic error of measurements, in particular in the case of the application of algorithm (9).
- application of the calibration algorithm (9) allowed not only for the correction of the slope of the static characteristics but also for the shift in its zero. In result the maximum error does not exceed ±3.0 %.
- the random component of the weighing error was limited by the use of averaging of results obtained from four load sensors. After calibration, the error $\delta_{0.95}$ (the error for which the probability of exceeding this amount is 0.05) is identical for both systems, amounting to 2.1 %, which should be understood as a good result. Further reduction of the random component of error would require increasing the number of load sensors installed at each system.

The experiments described here are planned to be repeated after six months, allowing for the acquisition of more knowledge on the metrological properties of the HS-WIM systems.

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