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ACCURACY ANALYSIS OF WIM SYSTEMS CALIBRATED USING PRE-WEIGHED VEHICLES METHOD

Accuracy of WIM (Weigh-In-Motion) systems depends on several factors, of particular importance is the calibration procedure. Parameters of the calibration process have essential influence on accuracy of weighing results. There are many calibration methods to be used for weighing systems. The pre-weighed calibration vehicles method is the most commonly applied, because it is simple and applicable to various classes of WIM systems. There are a few estimators of calibration coefficients possible to determine, according to the assumed criterion. This paper summarizes the results of estimator quality assessment, for a number of trucks and their passing cycles. Besides, the paper is intended to explore how parameters of the calibration process, the quality of the road surface, class and speed of calibration vehicles could influence the final accuracy of WIM systems. Such analysis requires a number of different tests in different conditions and is rather time consuming, that is why modelling and simulation methods were adopted instead.

Keywords: modelling and simulation, WIM, MS-WIM, calibration of WIM systems, pre-weighed vehicles method

1. INTRODUCTION

Accuracy of the WIM systems depends on several factors and the calibration procedure is of major importance. Calibration should be performed after sensors are installed in the road surface. Once a sensor is installed, the road surface becomes an element of the measurement system and its parameters will control the accuracy of weighing results. To calibrate any WIM system it is required that the experimental relationship (usually linear) be obtained between measurement data and reference values and relevant coefficients estimated. Thus the determined formula allows conversion of direct measurement data to the load exerted on the road surface by successive axles of the vehicle or to its total mass. For this reason the precision determination of the reference values (usually by static axle by axle pre-weighing of calibration vehicles) is very important. There are several calibration methods of weighing systems, i.e.: static calibration, automatic self-calibration, pre-weighed vehicles method, post-weighed vehicles method (vehicles from the traffic stream), methods using calibrated forces or shocks (simulating vehicle axle load) or instrumented vehicles method [1, 4, 5]. The choice of the calibration method depends on the purpose of measurement (static or dynamic component of the load, total mass etc.), type of used sensors (in widespread use nowadays are strain gages, capacitive, piezoelectric or quartz sensors) and technical conditions. Among these methods, the use of pre-weighed calibration trucks is the most commonly applied, because it is simple and applicable to different classes of WIM systems. There are a few estimators of calibration coefficients possible to determine, according to the assumed criterion (minimize the mean square error or bias error etc.).

The quality of these estimators was analyzed, depending on the number of calibration trucks and number of runs. Besides, the aim of the study is to explore how parameters of the calibration process, quality of the road surface, type and speed of calibration vehicles should affect the final accuracy of WIM systems (described according to COST 323 specifications). Two weighing systems were taken into consideration: the preselective two-sensor WIM system and the MS-WIM system equipped with sixteen sensors. Such analysis requires a large number of tests to be conducted in different conditions. In real traffic conditions these tests take a very long time. For that reason modelling and simulation methods were applied.

2. CALIBRATION METHODS

After installation every WIM system should be initially calibrated before being put to use. The accuracy of final data in such systems greatly depends on the procedure and conditions of the calibration process [1]. Of particular importance is the selection of reference values and the accuracy should be in agreement with the expected accuracy of the calibrated WIM system. The choice of the calibration method depends on the purpose of measurement, type of sensors, applications, user requirements and technical conditions. Several calibration methods of WIM systems are available nowadays [1, 4, 5]:

- **static calibration** – possible only in the systems utilising sensors that allow static weighing. This method does not take into account pavement conditions and road-vehicle interactions. It is convenient for low speed WIM systems.
- **use of shock or pressure devices** – whereby sensors are subjected to repeatable shocks or pressure variations. The method is independent of pavement characteristics, vehicle parameters and its speed or load. It should be used for impact force measurements.
- **calibration by instrumented vehicle** – intended for systems measuring axle impact forces or for MS-WIM systems. This method allows calibration on the basis of real values actually measured by WIM systems. Major drawbacks of this method are:

high costs, problems with data synchronization, technical difficulties. The calibration quality depends on the accuracy of the instrumented vehicle.

– **automatic self-calibration** – intended for permanent automatic recalibration of WIM systems and for correction of any bias and trends of weighing sensors, pavement, electronics or external influences e.g. temperature changes. It requires good *a'priori* knowledge of traffic conditions in WIM site localization and "reference vehicles" which should be taken from the traffic stream. The efficiency of this method depends on this knowledge and traffic intensity.
– **pre-weighed calibration vehicles method** – recommended when the WIM system is designed to estimate the static axle load or total mass of vehicles. It is suitable for various WIM system structures. In this method calibration (pre-weighed) vehicles pass many times over the WIM system. Road-vehicle interactions are partially eliminated though the method is sensitive to the calibration vehicle characteristics.

3. ESTIMATORS OF CALIBRATION COEFFICIENTS

Typically, the pre-weighed calibration vehicles method requires the use of several calibration trucks with known masses and static axle loads, that repeatedly pass the calibration site at different speeds. In this case, the static weighing results and results obtained from the WIM system become the basis for calculation of calibration coefficients. The general linear formula between static and dynamic weighing results is given as:

$$Wd_{i,k} = \frac{1}{C} Ws_k + b, \tag{1}$$

where: $Wd_{i,k}$ – dynamic weight for k^{th} vehicle in i^{th} run, Ws_k – static weight of k^{th} vehicle, and C, b are calibration coefficients that should be estimated. Several estimators of calibration coefficients can be determined, depending on the assumed criterion (minimizing mean square error, minimizing bias error etc.). In [1] four estimators are proposed. A widely applied coefficient C is only estimated (though obligatory whenever only one calibration vehicle is used). In terms of minimization of the mean square error and $b = 0$, the estimator of the calibration coefficient has the form [1]:

$$C_1 = \frac{\sum\limits_{k=1}^{K} n_k \left(Ws_k\right)^2}{\sum\limits_{k=1}^{K} \left(Ws_k \sum\limits_{i=1}^{n_k} Wd_{i,k}\right)}, \tag{2}$$

where: n_k – number of runs of k^{th} vehicle, K – number of pre-weighed vehicles. Minimizing the total bias error for all calibration vehicles, the estimator of calibration coefficient has the form:

$$C_2 = \frac{\sum\limits_{k=1}^{K} n_k W s_k}{\sum\limits_{k=1}^{K} \sum\limits_{i=1}^{n_k} W d_{i,k}}. \tag{3}$$

Minimizing the bias error for each calibration vehicle, the estimator is expressed as:

$$C_3 = \frac{\sum\limits_{k=1}^{K} n_k}{\sum\limits_{k=1}^{K} \sum\limits_{i=1}^{n_k} \left(\frac{W d_{i,k}}{W s_k} \right)}. \tag{4}$$

In the case of total mean square error minimization, for all calibration vehicles and for $b \neq 0$, the estimators of calibration coefficients have the forms:

$$\begin{aligned} C_4 &= \frac{\left(\sum\limits_{k=1}^{K} n_k\right)\left(\sum\limits_{k=1}^{K} n_k (W s_k)^2\right) - \left(\sum\limits_{k=1}^{K} n_k W s_k\right)^2}{\left(\sum\limits_{k=1}^{K} n_k\right)\left(\sum\limits_{k=1}^{K} \sum\limits_{i=1}^{n_k} W s_k W d_{i,k}\right) - \left(\sum\limits_{k=1}^{K} n_k W s_k\right)\left(\sum\limits_{k=1}^{K} \sum\limits_{i=1}^{n_k} W d_{i,k}\right)}, \\ b &= \frac{\left(\sum\limits_{k=1}^{K} n_k (W s_k)^2\right)\left(\sum\limits_{k=1}^{K} \sum\limits_{i=1}^{n_k} W d_{i,k}\right) - \left(\sum\limits_{k=1}^{K} n_k W s_k\right)\left(\sum\limits_{k=1}^{K} \sum\limits_{i=1}^{n_k} W s_k W d_{i,k}\right)}{\left(\sum\limits_{k=1}^{K} n_k\right)\left(\sum\limits_{k=1}^{K} n_k (W s_k)^2\right) - \left(\sum\limits_{k=1}^{K} n_k W s_k\right)^2}. \end{aligned} \tag{5}$$

The estimators (5) can be used only for more than one calibration vehicle.

4. MODELS OF ROAD SURFACE AND VEHICLE SUSPENSION

The main reason why the accuracy of WIM systems is limited (both at the calibration stage and during routine operation) is the occurrence of a dynamic component in the signal of the vehicle axle load exerted on the road surface. The amplitude of this component depends on the pavement quality, vehicle speed and suspension characteristics and may even amount to 40% of the static axle load value. The accuracy of the WIM system depends also on parameters of the applied sensors (heterogeneous sensitivity characteristic, temperature etc.) [3, 4, 6]. An analysis of the influence of the calibration process on WIM system accuracy in normal traffic is difficult because of the large number of tests that should be performed and the long time they take. That is why the accuracy of selected WIM systems is assessed in relevant simulation tests. To ensure reliable results, it is required that dynamic vehicle models as well as the road surface profiles, sensor characteristics and system structure be taken into account.

Two weighing systems were taken into consideration: a classical preselective WIM system with two sensors and a MS-WIM system equipped with sixteen sensors. Both systems utilize piezoelectric sensors distributed uniformly every 1.0 meter.

The properties of each load sensor were modelled by the irregularity of its sensitivity. On the basis of manufacturer's specification of piezoelectric sensors (MSI), different sensitivity was assumed along each sensor (in the range ±7%).

The method of pavement modelling was adopted utilising spectral descriptions of road profiles [2, 8]. The road profile may be generated using the inverse discrete Fourier transform, in accordance to the formula:

$$u_r = \sum_{k=0}^{N-1} \sqrt{S_k} e^{i\left(\varphi_k + \frac{2\pi kr}{N}\right)} \qquad r = 0, 1 \ldots (N-1), \tag{6}$$

where: $S_k = (2\pi/N\Delta)S_{11}(\gamma_k)$; $S_{11}(\gamma_k)$ – target spectral density; $\gamma_k = 2\pi k/N\Delta$ – wave number [rad/m]; Δ – distance interval between profile coordinates; φ_k – set of random phase angles, uniformly distributed between 0 and 2π; u_r – series of spot heights at regular intervals. Thus generated road profile does not represent any part of a real road, but only a given type of road (good, very good etc.). It reflects the statistical properties of a pavement with a given quality, defined by the target spectral density. As each vehicle can run along a different path, 500 correlated profiles were prepared (500 implementations of profiles corresponding to the assumed identical statistical parameters) for roads of "good" and "average" surface quality (spectral density equal to 20 and $120/10^{-6}$ m^3/cycle respectively for the first wave [2]). The "average" road surface quality was chosen in strong contrast to "good" road, thereby allowing the evaluation of applied models. Each profile was generated for a 500 m long road section. The WIM systems were located on the 450th meter of the road profile. Selected road surface profiles are shown in Fig. 1.

The behavior of a vehicle passing over the analyzed WIM systems was simulated using the "quarter car" model [2]. This simplified vehicle model generates a signal of the axle load exerted on the road surface. This signal includes both static and dynamic components with frequencies in the range 1.5 ÷ 4 [Hz]. It allows the determination of the values of forces exerted on successive sensors of the investigated WIM systems. The model structure and the diagram of spectral density of the dynamic part of the axle load, obtained from simulation are presented in Fig. 2.

The 'quarter – car' model includes two masses, a suspended (k_s, c_s) vehicle body mass m_s and unsuspended wheel mass m_u, both constrained to move vertically. The road profile displacement $u(t)$ is the input to this model. The model generates the main dynamic component of the force due to suspended mass balancing. The nominal parameters of the vehicle suspension model were defined according to [2].

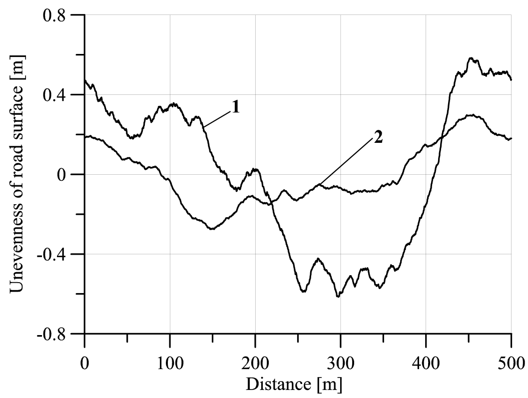

Fig. 1. Selected road surface profiles for: 1 – "average" road quality, 2 – "good" road quality.

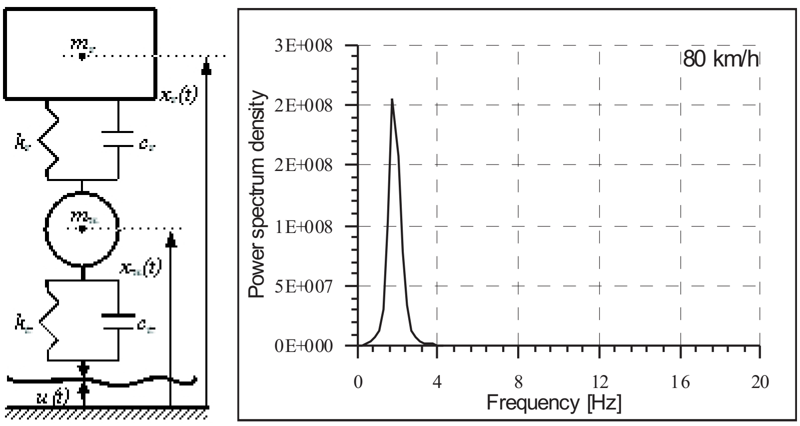

Fig. 2. Model structure and spectral density characteristic for a "quarter-car".

5. SIMULATION TESTS

Simulation tests used the models, sensor characteristics and system structures presented in the previous paragraph. Calibration of a WIM system is a stochastic process. It means that repetition of such process each time produces different values of calibration coefficients. Thus, the quality of estimators of calibration coefficients was examined depending on the number of calibration trucks and number of runs. The distribution of vehicle masses in the operating range of the weighing system was uniform. The standard deviation in relation to mean values of estimated coefficients was used to assess the estimators' quality. The characteristics of estimators (2), (3) and (4) determined in repeated simulations of the calibration process (500 times at each point), are presented in Fig. 3.

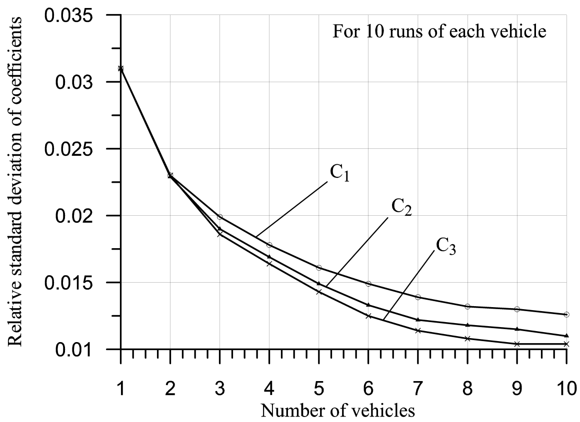

Fig. 3. Relative standard deviation of estimates of calibration coefficients versus number of calibration vehicles.

Theoretically as many calibration trucks should be used as possible. Simulation tests reveal that ten runs of each of the ten calibration trucks is enough to determine the calibration coefficients with standard deviation on the level of 1% of their mean values. In the case when only one calibrated vehicle is used, all estimators yield the same result. The assessment of WIM systems accuracy involves two steps: determination of calibration coefficients in accordance to formulas (2), (3), (4) and (5) for both considered weighing systems and validation of the systems accuracy. The main point was to determine how the parameters of the calibration method (type of estimator, number of calibration trucks and number of runs of each of them), quality of road surface and the speed of calibration and test vehicles could influence the accuracy of WIM systems with two and sixteen sensors.

Calibration coefficients were determined using seven calibration trucks. At this stage the parameters of vehicle models (see Fig. 2) were chosen randomly (with uniform distribution) in the range of ±10% of their nominal values. The static axle loads were distributed uniformly in the range of 50 ÷ 150kN. Each calibration truck travelled over the system 300 times with a randomly chosen road profile prepared before (correlated profiles corresponding to the same assumed statistical parameters) and at given constant speed. The profiles differ only in detail (in higher frequency components) because of different paths of vehicle runs. The calibration coefficients were determined for whole systems (not for each sensor separately).

In the second stage the accuracy of both weighing systems was analyzed. The assessment of system quality is based on estimation of the r.m.s. error of static load, in accordance to the formula:

$$\delta_{RMS} = \sqrt{\frac{1}{N}\sum_{j=1}^{N}\left[\frac{\left(Wd_j - Ws_j\right)}{Ws_j}\right]^2}, \tag{7}$$

where: Wd_j, Ws_j – dynamic and static weight of the test vehicle in j^{th} subsequent run, N – total number of test runs. At the same time, the WIM systems accuracy was determined in accordance with COST 323 specifications. The validation tests were performed using 500 vehicles. Model parameters were chosen randomly in the range of ± 30% of their nominal values. Vehicle speed and gross weight were also selected at random, from the ranges 20 ÷ 80km/h and 50 ÷ 150 kN respectively, and so was the road surface profile (like in the calibration stage). The results of WIM systems accuracy assessment are presented in figures versus speed of calibration vehicles (i.e. each point of the characteristics was determined by way of system calibration using vehicles running at constant speed). Vehicles travelling at different speeds in the whole assumed range were considered in the validation procedure. Figure 4 shows results obtained for a system with two sensors and for two road surface quality levels. Characteristics 1 and 2 are obtained for the "average road quality" and for estimators (2), (3), (4) and (5) respectively, while characteristics 3 and 4 were collected for "good" quality roads. It is worthwhile to notice that the application of estimator (5) provides better results in this case (characteristics 2 and 4) than other estimators.

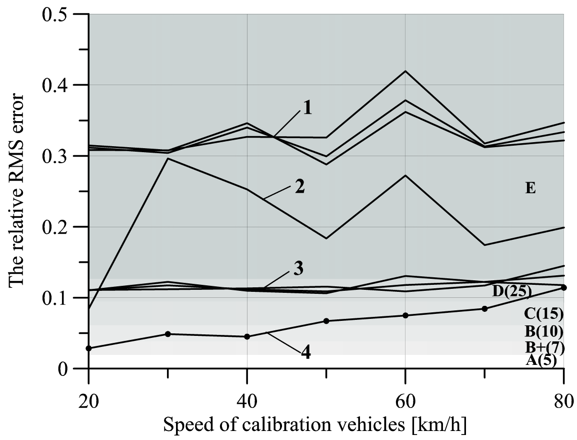

Fig. 4. Relative RMS errors and COST 323 class specification for a WIM system with two sensors located in a road with "average" and "good" quality.

Figure 5 presents results of a similar analysis for a MS-WIM system equipped with 16 sensors. The characteristics 1 were obtained for "average" road quality and characteristics 2 for a "good" road. The error value is strongly dependent on road quality and practically independent on the type of calibration coefficients estimator.

For roads with the worst quality we observe an increase of error values at higher speeds of calibration vehicles.

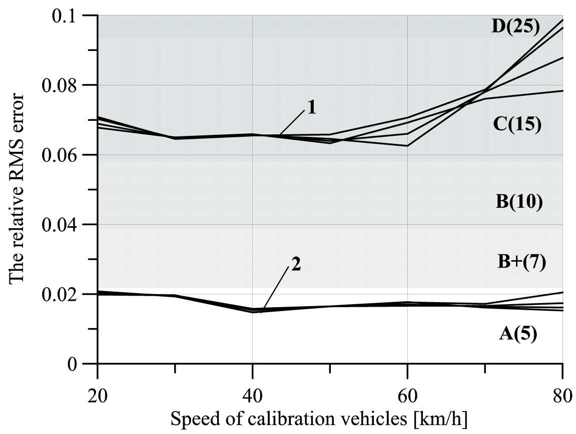

Fig. 5. Relative RMS errors and COST 323 class specification for a MS-WIM system with sixteen sensors located in a road with "average" and "good" quality.

Figure 6 compiles the characteristics collected for systems with two and sixteen sensors and for "good" quality of the road surface. Characteristics 1 was obtained for a system with two sensors and estimators (2), (3), (4), characteristics 2 has relevance to the same system and estimator (5). Characteristics 3 shows the results obtained for a system with 16 sensors. It is worthwhile to notice that two-sensor systems calibrated in accordance to the estimator (5), for calibration vehicles moving at low speeds, produce results comparable to systems with a higher number of employed sensors.

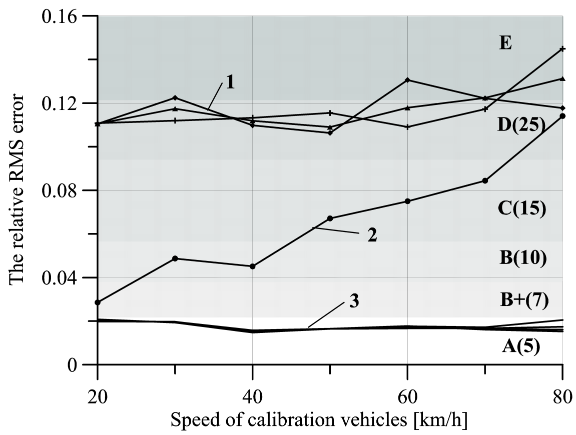

Fig. 6. Relative RMS errors and COST 323 class specification for systems with two and sixteen sensors, located in a road with "good" quality.

Figure 7 presents results obtained for a WIM system with 16 sensors calibrated at a given constant speed of calibration vehicles and for a "good" quality road (characteristics 1), and results obtained for the same system calibrated using vehicles running at different speeds in the range of 20–80 km/h (characteristics 2).

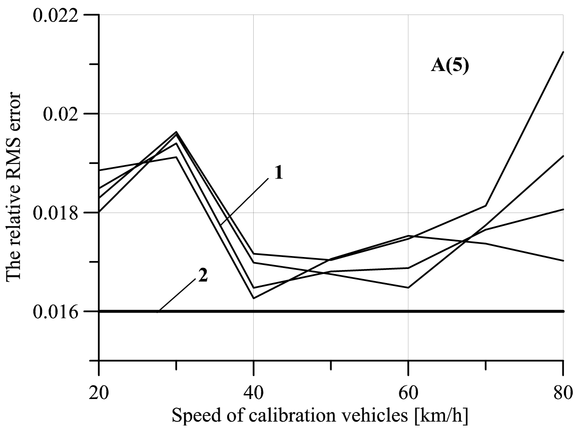

Fig. 7. Comparison of accuracy of a system calibrated with constant speed (characteristics 1) and system calibrated with different speeds (characteristic 2).

6. CONCLUSIONS

The paper summarizes accuracy assessment data of two types of WIM systems (with two and sixteen sensors respectively) calibrated by the pre-weighed vehicles method. The analysis was conducted using simulation methods. Four estimators of calibration coefficients were taken into consideration. The influence of calibration parameters (number of pre-weighed vehicles, number of runs, speeds), quality of road surface and system structure were analyzed. Simulation tests reveal that ten runs of each of ten calibration trucks are sufficient to determine the calibration coefficients with standard deviation on the level 1% of their mean values. When only one calibrated vehicle was considered, all estimators gave the same result. For both considered systems the errors of vehicle total mass estimation was about three times higher for "average" than for "good" road (exemplary for the MS-WIM system: "good" road – 2%, "average" road – 7%). For a two-sensor system the errors were about five times higher than for a system with sixteen sensors, for the same road quality. Of critical importance is vehicle speed selection at the calibration stage, particularly for roads of worse quality. It is worthwhile to notice that estimator (5) used in a two-sensor system calibrated at low speeds gives results comparable to systems with higher number of sensors. Simulation tests run for a system with 16 sensors confirm that the calibration process should be realized using vehicles running at different speeds in the whole expected range of the WIM system. In the case of calibration with constant speed it is necessary to choose a speed in the middle of the speed range. Simulation data, even those obtained using simplified models, are comparable to results from real tests [7, 9]. They confirm that in the area of weighing in motion and calibration of such systems, modelling and simulation are an effective tool ensuring reliable results.

REFERENCES

1. Final Report of Project COST 323 on Weigh-in-Motion of Road Vehicles; edit.: B. Jacob, E.J. O'Brien, S. Jehaes, Paris 2002.
2. Cebon D.: *Handbook of Vehicle-Road Interaction*. Swets & Zeitlinger B.V., Lisse, the Netherlands 1999.
3. Scheuter F.: *Evaluation of Factors Affecting WIM System Accuracy*. Pre-proc. of 2nd European Conference of Weigh in Motion of Road Vehicles, Lisbon 1998, pp. 371–377.
4. Huhtala M.: *Factors Affecting Calibration Effectiveness*. Proc. of the final symposium of the project WAVE, Paris 1999.
5. Stańczyk D.: *New Calibration Procedure by Axle Rank*. Proc. of the final symposium of the project WAVE, Paris 1999.
6. Jacob B., Stanczyk D.: *Calibration of Highly Accurate WIM System for Legal Application*. Proc. of the Final Symposium of the Project WAVE, Paris 1999, pp. 55–68.
7. Burnos P., Gajda J., Piwowar P., Sroka R., Stencel M., Zeglen T.: *Multi-Sensor Weigh in Motion System*. Proc. of International Conference on Heavy Vehicles, Paris 2008.
8. ISO8608 (1995) *Mechanical vibration – Road surface profiles* – Reporting of measured data.
9. Burnos P., Gajda J., Piwowar P., Sroka R., Stencel M., Zeglen T.: *Measurements of Road Traffic Parameters Using Inductive Loops and Piezoelectric Sensors*. Metrology and MS, vol. XIV, no. 2, 2007, pp. 187–203.