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ACCURATE WEIGHING OF MOVING VEHICLES

The paper deals with real-time Multi-Sensor Weigh – In – Motion System (MS-WIM). This system was designed in Poland in a period of 3 years from 2003 to 2006. The embodied system is equipped with 16 piezoelectric load sensors, in the form of narrow 4m long strips, provided by Measurement Specialties. The paper outlines the system structure and its elements i.e. the weighing site, the data acquisition system and data processing software. Experimental tests indicate that the designed MS-WIM system falls in accuracy class B+(7) in the speed range from 30 km/h to 80 km/h.

Keywords: WIM (weigh-in-motion), multiple sensors (MS) WIM, accuracy analysis

1. INTRODUCTION

High-speed WIM systems are widely used throughout Europe. The number of preselective HS-WIM systems used at present in Poland is roughly 20–25. The purpose of this paper is to check whether real-time weighing of moving vehicles can be effected with the accuracy comparable to static scales. This accuracy is strongly affected by road surface roughness, the type and number of load sensors, distances between them, as well as a static load estimation algorithm. The influence of all these factors on WIM systems accuracy was analyzed and tested using the modeling methods, simulations and field tests.

2. MS-WIM SITE DESIGN

In the first place, the design of the MS-WIM site depends on the choice of load sensors number and the distances between successive sensors, which should ensure the desired weighing accuracy. In this case the required accuracy of the MS-WIM system was taken to be 2–4%, in terms of relative standard deviation of the weighing result. The number of sensors was taken to be 16.

The “input” parameters of the design process are the speed range of the weighed vehicles, vehicle class and their mechanical parameters, as well as quality of the road surface. The design process was supported by modeling and simulation tests of the vehicle – road interactions.

According to the WIM site design method proposed in [3], the following assumptions were made:

1. Load sensors are uniformly distributed along the WIM site.
2. Static axle load is computed as a simple average value of the load samples from successive sensors.
3. Measurement signal (load) is generated by the weighed vehicle, whose mechanical properties are described by its transfer function $H(j\omega)$.
4. Vehicle mechanics is excited by road surface roughness characterized by its displacement spectral density $S_u(k)$ according to the model proposed in [12].
5. Load force travels along the WIM site equipped with n load sensors distant from one another by Δ.
6. Load sensors are idealized, without any disturbances and internal errors.

These assumptions allow the theoretical evaluation of the MS-WIM system quality in the form of a relative error (1).

$$\rho(n) = \frac{\sigma(n)}{P_0}, \tag{1}$$

where: $\sigma(n)$ – standard deviation of the error of static load or gross weight estimate, P_0 – static axle load or gross weight.

The rough estimate of the load sensor distances may by based on the formulas presented in [3]:

$$\Delta = \frac{2(n-1)\bar{V}}{\bar{f}n^2}, \tag{2}$$

where: $\bar{V}$ – average speed of the weighed vehicles in [m/s], $\bar{f}$ – eigenfrequency of the vehicle mechanics, n – number of load sensors. Assuming $\bar{V}$ = 50 km/h = 13.89 m/s, $n = 16$ and $\bar{f} = 2$ Hz, the distance between load sensors Δ is equal to 0.926 m.

Simulation tests utilized the model of road surface in the form of its spectral power density (3) proposed in [4] and the model of the vehicle mechanics in the form of its mechanical transfer function.

$$S_u(k) = \begin{cases} S_u(k_0)\left(\dfrac{k}{k_0}\right)^{-n_1} & \dfrac{k}{k_0} \le 1 \\ S_u(k_0)\left(\dfrac{k}{k_0}\right)^{-n_2} & \dfrac{k}{k_0} > 1 \end{cases}, \tag{3}$$

where: k – wavenumber, k_0 – datum wavenumber, $k_0 = 1/(2\pi)$ cycles/m, n_1, n_2 – constant coefficients, $n_1 = 3$, $n_2 = 2.25$, $S_u(k_0)$ – spectral density at k_0. The assumed constant value $S_u(k_0) = 30 \times 10^{-6}$ m^3/cycle corresponds to a good/average road class. The mechanical transfer function of the simulated vehicle describes the so-called quarter model with the eigenfrequency equal to 2 Hz [14].

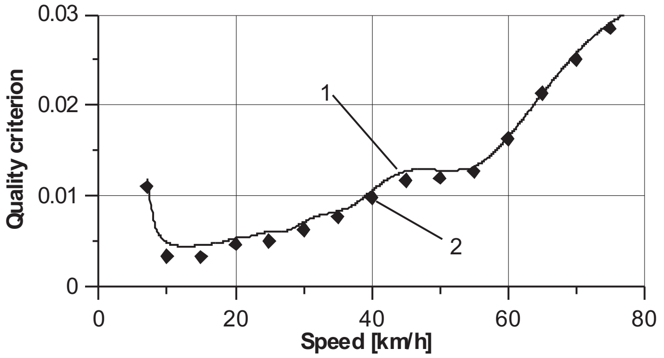

Fig. 1. Quality characteristics of the MS-WIM system vs. vehicle speed. 1 – analytical characteristic, 2 – points calculated in the simulation tests.

The MS-WIM quality criterion (1) calculated analytically and as the result of simulation of the models of WIM site, road surface roughness, vehicle mechanics and gross weight estimation algorithm is presented in Fig. 1. The simulation tests were described in [14]. These characteristics confirm that in the assumed speed range and for load sensors distant from one another by 1m, the designed MS-WIM system meets the accuracy requirement.

3. MS-WIM SYSTEM ARCHITECTURE

The designed MS-WIM system is equipped with 16 piezoelectric strip sensors provided by Measurement Specialties, 8 inductive loop sensors and 2 temperature sensors as shown in Fig. 2.

The piezoelectric load sensors are uniformly distributed along the WIM site at a distance of 1m from one another. Each pair of load sensors is surrounded by one inductive loop sensor, creating a single two-sensor WIM subsystem. Each subsystem is additionally equipped with analog-digital data acquisition and data processing systems. Hence, the designed MS-WIM system includes 8 such subsystems. The data processing algorithm implemented in the subsystems involves sampling of the voltage signal of each load sensor (the sampling frequency is equal to 10kHz), estimation of load exerted by successive axles of weighed vehicle on a single load sensor in accordance with the formula given in manufacturer's specification, calibration of the load measurement results according to the calibration coefficients and temperature correction, taking into account the current asphalt temperature measurement data. All subsystems are additionally equipped with a clock synchronizing the sampling moments and time interval measurements. Moreover, they classify the vehicle, basing on the number of axles, and distances between successive axles and speed estimates. Measurement of the successive axle speed in each subsystem allows evaluation of this speed changeability along the WIM site. Weighing results obtained for speed variability exceeding the specified limit are neglected.

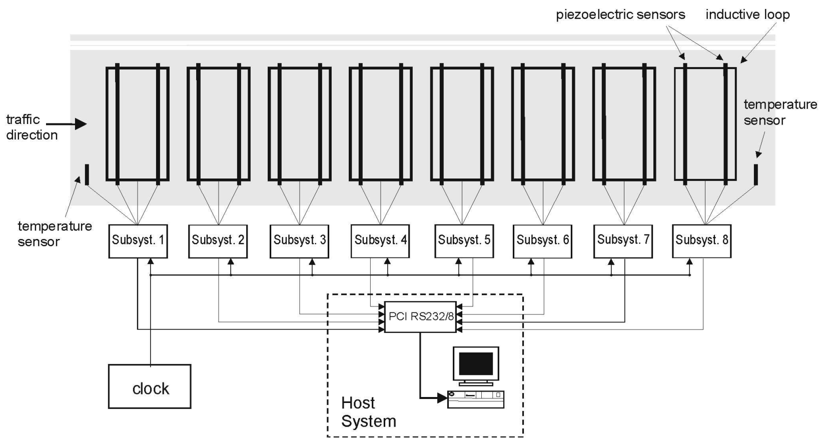

Fig. 2. Multi-Sensor WIM site.

The measurement data in the form of sets of two load samples (from two load sensors operated by a single subsystem) corresponding to each axle of the weighed vehicle, time moments of their sampling, vehicle speed, number of axles, axles' distances, vehicle length are transferred by a PCI RS232/8 interface to the host system (PC computer). The host system queues the data according to the sampling moments and completes the sequence of 16 load samples corresponding to each vehicle axle. Then the chosen estimation algorithms of the static loads of all axles and gross weight are executed. The weighing results and measurement results of other parameters characterizing the weighed vehicle are displayed on the monitor and stored in memory.

4. DATA PROCESSING ALGORITHMS

Basing on the analysis of pavement models [5, 6] and selected models of vehicle suspensions, it is reasonable to suppose that the following relationship is a good approximation of the force the vehicle wheels exert on the pavement during vehicle motion:

$$P(t) = P_0 + \sum_{k=1}^{M} P_k \sin(2\pi f_k t + \varphi_k), \tag{4}$$

where: P_0 – static load exerted on the road by a stationary vehicle, M – number of dynamic components of the load signal, P_k, f_k, φ_k – parameters of the dynamic load components: amplitude, frequency and phase angle, respectively.

Depending on the required modeling accuracy and vehicle suspension design, different numbers M of dynamic components (usually $M = 1$ or $M = 2$) are defined in the model. Frequencies f_1 and f_2 in this model describe the vertical balancing of the suspended vehicle mass and wheel hopping, respectively. Depending on the vehicle class and vehicle gross weight, these frequencies are included in the range $f_1 = 1.5 \div 4.5$ Hz and $f_2 = 8 \div 15$ Hz, respectively. The amplitudes of individual dynamic components are significantly dependent on the vehicle speed. The purpose of the estimation algorithms implemented in WIM systems is to estimate the static loads P_0 of each axle of weighed vehicle with sufficient accuracy. These algorithms are based on the load signal samples measured by all load sensors in the considered MS-WIM system.

In the described MS-WIM system two estimation algorithms of the static load were implemented. They are: a simple algorithm averaging the load signal samples p_1, $p_2, \ldots, p_n$ obtained from successive load sensors (Mean) and the maximum likelihood algorithm.

The maximum likelihood estimator (ML) of the static component P_0 was proposed in [7, 13], based on the underlying assumption that load measurement results on successive load sensors $p_1, p_2, \ldots, p_n$ are uncorrelated and corrupted by additive, normally distributed disturbances $\boldsymbol{\varepsilon}$, and with zero expected value and standard deviation σ. These assumptions yield the likelihood function in the form of (5).

$$g(\boldsymbol{\varepsilon}) = g(\boldsymbol{p}/\boldsymbol{b}) = \left(\frac{1}{\sqrt{2\pi}\sigma}\right)^n e^{-\frac{\sum\limits_{i=1}^{n}\left[p_i - P_0 - \sum\limits_{k=1}^{M} P_k \sin(2\pi f_k t_i + \varphi_k)\right]^2}{2\sigma^2}}, \tag{5}$$

where: n is the number of load sensors in the MS-WIM system and $g(\cdot)$ is the probability density function.

The model coefficients vector $\boldsymbol{b}$ for $M = 2$ includes five components and is in the form (6).

$$\boldsymbol{b} = \begin{bmatrix} P_0 & P_1 \sin\varphi_1 & P_1 \cos\varphi_1 & P_2 \sin\varphi_2 & P_2 \cos\varphi_2 \end{bmatrix}. \tag{6}$$

Solution of the estimation task involves searching for such values of vector components $\boldsymbol{b}$, which should maximize the likelihood function (5). This problem is equivalent to the minimization of the expression (7).

$$L(\boldsymbol{b}) = \sum_{i=1}^{n}\left[p_i - P_0 - \sum_{k=1}^{M} P_k \sin(2\pi f_k t_i + \varphi_k)\right]^2. \tag{7}$$

Considering that

$$\boldsymbol{X} = \begin{bmatrix} 1 & \cos(2\pi f_1 t_1) & \sin(2\pi f_1 t_1) & \cos(2\pi f_2 t_1) & \sin(2\pi f_2 t_1) \\ 1 & \cos(2\pi f_1 t_2) & \sin(2\pi f_1 t_2) & \cos(2\pi f_2 t_2) & \sin(2\pi f_2 t_2) \\ 1 & \cos(2\pi f_1 t_3) & \sin(2\pi f_1 t_3) & \cos(2\pi f_2 t_3) & \sin(2\pi f_2 t_3) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & \cos(2\pi f_1 t_n) & \sin(2\pi f_1 t_n) & \cos(2\pi f_2 t_n) & \sin(2\pi f_2 t_n) \end{bmatrix}, \tag{8}$$

the expression (7) may be rewritten as (9).

$$L(\boldsymbol{b}) = \sum_{i=1}^{n} [p_i - \boldsymbol{X}\boldsymbol{b}]^2. \tag{9}$$

Assuming the frequencies f_1, f_2 to be known, the values of model coefficients are sought that minimize the functional (9). As in practical applications, frequencies of dynamic components are not known a priori, the solution to the problem is being determined for each pair (f_1, f_2) of frequencies, selected with a predefined step from their variability intervals. The vector $\boldsymbol{b}$ components corresponding to each pair (f_1, f_2) are calculated in accordance with the formula (10).

$$\boldsymbol{b} = \left(\boldsymbol{X}^T\boldsymbol{X}\right)^{-1} \boldsymbol{X}^T\boldsymbol{p}. \tag{10}$$

Finally, the estimation process should yield such values of the sought vector $\boldsymbol{b}$ components and corresponding frequencies pair (f_1, f_2), that the functional (7) be minimal.

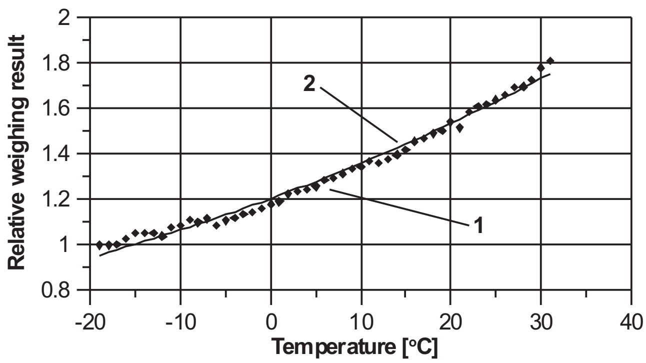

Fig. 3. Weighing result vs. asphalt temperature. 1 – experimental results, 2 – model.

The piezoelectric strip sensors used in this MS-WIM system are mounted under the asphalt surface. Asphalt transmits the load from the wheel to the sensors. Changes in the asphalt mechanical parameters vs. temperature cause correlated changes in the sensor sensitivity. From this point of view, the quartz load sensors have better metrological properties but they are much more expensive. The model describing sensor sensitivity changes vs. temperature was experimentally determined in the temperature range from −20°C up to +30°C. In this range temperature changes account for 80% changes of the weighing results. Figure 3 shows an experimental temperature characteristic of the WIM system equipped with piezoelectric load sensors. This characteristic is very well described by the model (11) proposed in [15].

$$C(Ta) = k_1 10^{w1(To-Ta)} \tag{11}$$

where: $k_1 = 3.8702$, $w1 = -0.0053$ [1/°C] – constant coefficients, $To = 45$ [°C] – reference temperature, Ta – current asphalt temperature. Model (11) is used for correction of the weighing results, basing on ongoing results of asphalt temperature measurements. This problem is discussed in detail in [2].

5. MS-WIM SYSTEM CALIBRATION

One of the main phenomena limiting the WIM system accuracy is spatial repeatability [8]. It is the tendency of the total tyre force paths of one axle to present similar patterns along the same road profile, over repeated runs. When several (statically pre-weighed) vehicles are used in calibration, with different suspensions, making repeated runs at different speeds and loads, then spatial repeatability is reduced to the statistical spatial repeatability and the obtained calibration factor is valid for more axles and vehicles.

The simple averaging procedure of gross weight estimation was implemented in the analyzed MS-WIM system. It leads to a significant simplification of the calibration procedure [9]. According to the European Specification COST323 proposal, one calibration (statically pre-weighed) vehicle (5 axle tractor with a semi-trailer) traveled the calibrated MS-WIM site 42 times at five different speeds (40 km/h, 50 km/h, 60 km/h, 70 km/h and 80 km/h) and its constant gross weight was equal to 32200 kg. The set of 21 measurement data were used for estimation of the calibration coefficient ensuring minimization of the bias error on the calibration vehicle gross weight. A second set of 21 measurement results was used to check the accuracy of the system.

6. ACCURACY ANALYSIS

An accuracy analysis of the designed MS-WIM system was conducted according to the procedure recommended in [10]. This procedure involves the estimation of the probability (i.e. confidence level) that an individual relative error of the WIM system falls in the centered interval $[-\delta; +\delta]$. A confidence interval width δ is defined for each distinguished WIM accuracy class.

The relative error in the discussed case was calculated for each measurement of the vehicle gross weight, in accordance with the formula (12).

$$x_i = \frac{(Wd_i - Ws_i)}{Ws_i}, \tag{12}$$

where Wd_i and Ws_i are measured weight-in-motion values and the reference (static) value respectively, expressed in the same units.

The lower bound of this confidence level (π) is given with a statistical risk α by (13).

$$\pi = \Phi(u_1) - \Phi(u_2), \tag{13}$$

where: $u_1 = (\delta - m)/s - t_{\nu,1-\alpha/2}/N^{1/2}$, $u_2 = (-\delta - m)/s + t_{\nu,1-\alpha/2}/N^{1/2}$, m, s – mean value and standard deviation of the sample of relative errors x_i, Φ – cumulative probability distribution function of a Student variable, $t_{\nu,1-\alpha/2}$ – Student variable with $\nu = N - 1$ degrees of freedom, N – number of measurements (sample size), α – statistical risk is taken to be 0.05.

The accuracy level of the WIM system is assessed by comparing the confidence level (13) to the minimum confidence level (π_0) required in accordance with the test and environmental conditions and the sample size. If $\pi \geq \pi_0$ the WIM system is accepted in the accuracy class defined by δ [11].

The procedure outlined above is valid as long as weighing errors are random and normally distributed. Because of the small number of measurement results, this hypothesis was not verified.

The accuracy of the designed MS-WIM system was tested during one day, with stable meteorological conditions, by using a single pre-weighed vehicle passing the tested WIM site 21 times at different speeds and with a constant gross weight. This fulfills the environmental repeatability conditions and full repeatability test conditions described in [10], which corresponds to the minimum confidence level $\pi_0 = 97.2$.

The results of the accuracy analysis are summarized in Table 1. The accuracy class of the designed MS-WIM system is B+(7) not far from the class A(5) if the maximum likelihood estimator of the vehicle gross weight was applied.

Table 1. Results of accuracy analysis of the considered MS-WIM system.

Estimation algorithm	Criterion	N	m (%)	s (%)	π_0 (%)	δ (%)	$\delta_{\min}$ (%)	π (%)	COST323
Mean value	Gross weight	21	−0.70	2.28	97.2	7	6.7	97.8	B+(7)
Maximum likelihood	Gross weight	21	−0.33	2.04	97.2	7	5.9	99.1	B+(7)

$\delta_{\min}$ – minimal confidence interval width corresponding to the equality $\pi_0 = \pi$.

The accuracy analysis procedure proposed by authors is also supported by the statistical analysis of the weighing errors using the characteristic (14) [1].

$$\Pr(|x|) = 1 - \Phi(|x|), \tag{14}$$

where: $|x|$ is the absolute value of the relative estimation error (12) of the vehicle gross weight and $\Phi(|x|)$ is the estimate of the cumulative probability function of this error, evaluated using the sample statistics.

The characteristic (14) gives the probability (Pr) that an error greater than $|x|$ should occur, and hence it is referred to as reliability characteristic. The characteristic (14) determined for the described MS-WIM system is presented in Fig. 4, leading us to the conclusion that during the accuracy test no vehicle was weighed with an error greater than 4%.

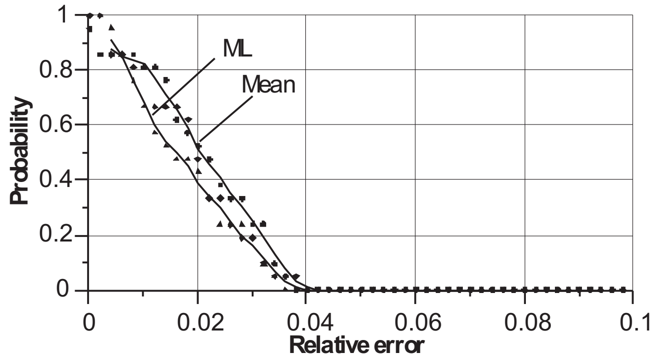

Fig. 4. Reliability characteristic of the WIM system. These characteristics correspond to different algorithms of gross weigh estimation: mean value of the measurement results of separate sensors (Mean) and maximum likelihood estimator (ML) respectively.

7. CONCLUSIONS

The described MS-WIM system was designed and constructed in the course of a three-year project sponsored by the Polish Ministry of Science and High Education. Because of financial limitations, that system was equipped with piezoelectric instead of quartz sensors. In consequence, the temperature dependence of sensor sensitivity, as well as sensors' internal errors limit the accuracy of the system. Nevertheless, it was well proven that the MS-WIM system accuracy can be comparable with that offered by a static scale.

Metrological properties of the system were experimentally explored and evaluated using the COST323 Standards and the reliability characteristic. The designed MS-WIM system is in accuracy class B+(7) and during the conducted tests the maximum error of gross weight measurement did not exceed 4%.

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