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NEW FUNCTIONALITIES OF THE WEIGH-IN-MOTION SYSTEM: iWIM SOLUTION

Summary. This paper presents new functionalities for systems weighing vehicles in motion, which result from the integration of various measurement technologies and the use of a precise registration and data processing system. The utilized registration track provides accurate measurements of basic vehicle parameters such as axle load and vehicle speed and makes it possible to determine the location of the vehicle passing the weighing station, calculate the width of the tire tread, and detect twin (double) wheels. A key functionality is the assessment of the reliability of the measurement, taking into account, among other factors, vehicle movement dynamics and the ambient conditions during the measurements. For this purpose, additional measurements of road surface temperature and wind speed and direction were introduced. The technological solutions used and the proprietary data processing algorithms are described. Tests carried out to verify the effectiveness of the proposed algorithms and to assess the significance of the influence of the isolated factors permitted confirmation of the validity of the proposed solutions.

1. INTRODUCTION

The use of overloaded vehicles on public roads has a negative impact on traffic safety and road infrastructure, in particular for roads and road engineering structures, such as bridges and viaducts. Exceeding permissible loads increases road surface degradation [1]. In the case of light-duty vehicles, the elimination of overloaded vehicles improves, above all, road safety.

In Poland, the elimination of overloaded vehicles from traffic is currently mainly handled by an entity called Road Transport Inspection (Inspekcja Transportu Drogowego – ITD). The procedure used by the ITD is that WIM (weigh-in-motion) stations (to be precise, high-speed WIM systems that do not impose any speed limit on the vehicle being weighed) are used for preselection (i.e., indicating vehicles that likely exceed their maximum permissible total mass or axle load limits). Selected vehicles are verified at the ITD inspection station. The accuracy and reliability of measurements are important parameters for preselection systems for weighing vehicles in motion. Incorrect system indications result in poor control system performance. On the one hand, they lead to a time-consuming procedure of the static

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weighing of vehicles that do not actually exceed the permitted values; on the other hand, they may result in genuine violations not being detected. These situations are very often related to the lack of consideration of dynamic factors and environmental conditions in current WIM technologies. Several additional limitations associated with the operation of WIM systems were pointed out in [2].

WIM systems are also used in many countries other than Poland [3]. This is because, in recent years, they have been the subject of a range of research and development work. In such studies, the functionality of the WIM as a whole, as well as its individual elements, are considered. WIM measurements' accuracy is affected by many factors, including vehicle dynamics, aerodynamic forces, site parameters, and sensor installation [4]. A particularly detailed role is played by load sensors installed in the roadway. Sensors based on various technologies are used in high-speed WIM systems. The construction and operating characteristics of the most commonly used load sensors are discussed elsewhere ([5] and [6], among others).

The effect of the temperature of the road surface and vehicle speed on load measurements for sensors of various technical types was analyzed in [7]. Dynamic phenomena originating from the suspension system of a vehicle in motion are one of the most relevant factors disrupting pressure measurements. One of the recently proposed solutions to this problem is the use of multiple (dozens of) point sensors (disks) distributed in several rows [8]. In [9, 10], other important issues were addressed, namely issues connected with the impact of the condition of the road surface and the quality of sensor mounting on the accuracy of axle weight measurements.

The literature contains a number of proposed ways to reduce WIM errors. Some, such as the one presented in [11], are based on the use of special signal-processing algorithms. Another direction applied in installations with classic linear load sensors is the construction of multi-sensor installations. They require the development of dedicated algorithms, whose task is to minimize the effect of vehicular motion dynamics, including the spatial repeatability of vehicle axle dynamics [12-14]. Neural networks (among others) show an aptitude for identifying the spatial repeatability of vehicle axle dynamics with the simultaneous elimination of noise from measurement signals [15]. An example of the use of a neural network integrating identification and prediction to increase the measurement accuracy of a multi-sensor system is presented in [8].

Both inductive loops and magnetic sensors are used to detect the presence of vehicles. The use of loops also makes it possible to determine vehicles' speeds and estimate their length. Hence, a two inductive loops are most commonly used at WIM stations, although solutions with more sensors exist (e.g., the Fareco system) [16]. From the point of view of the solution that is the subject of this publication, it is important to determine where the wheel passes through the sensor, as well as to detect double wheels. The literature does not devote much attention to these issues. Estimation of tire width using a fiber optic sensor measurement system is considered in some works [17, 18].

2. MATERIALS AND METHODOLOGY

2.1. Utilized technologies

In order to conduct the research, a newly developed system for recording and processing measurement data was installed at the station. This system made use of precision analog-to-digital converters and FPGA (field-programmable gate array) programmable circuits. This solution facilitates the processing and integration of signals from strain gauge load sensors, inductive loops, and additional piezoelectric polymer sensors within a single device (Fig. 1). Existing solutions require several processing devices and do not provide low-level processing capabilities for analog signals. In addition, through the use of a dedicated unit (industrial computer), the newly developed system enables the integration of signals from meteorological sensors and digital cameras.

Examples of recorded waveforms of integrated signals within the time window for a single passage (crossing event) of a five-axle vehicle are shown in Fig. 2. The sampling rates used are 31,250 Hz for signals from the load sensors (strain gauges) and piezoelectric sensors and 3125 Hz for signals from the inductive loops.

The signal waveforms presented in Fig. 2 were recorded using four strain gauge load sensors placed in pairs in two lines perpendicular to the road axis, two piezoelectric sensors placed at a 45° angle to the road axis to record the signal for the left and right wheels of the vehicle, and two induction loops placed successively to read the magnetic signature of the vehicle.

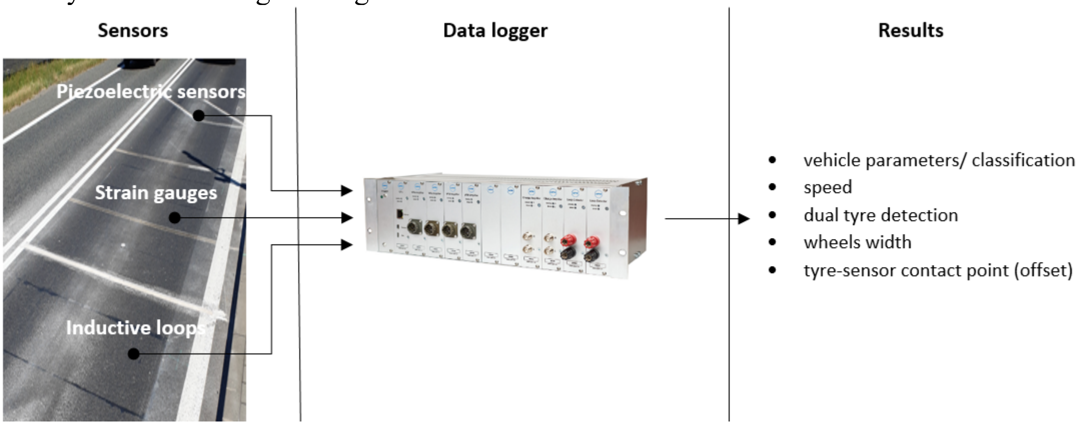


Fig. 1. Data processing within the iWIM system

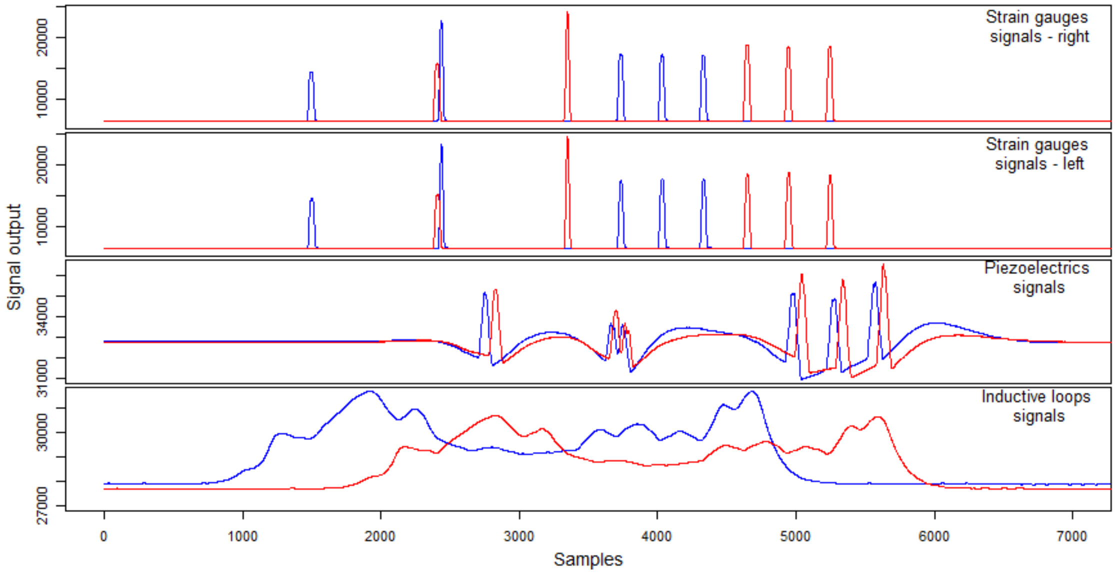


Fig. 2. Signal waveforms integrated into one time window for the single passage of a five-axle vehicle

2.2. Algorithms for processing measurement data

Algorithms that increase the functionality of previously used weighing stations for vehicles in traffic in Poland are an important new element of the data recording system. The introduction of new functionalities required the development and verification of a method for determining how a vehicle passes the measuring station, a method for determining the tire width, and methods for detecting a double wheel. In addition, on the basis of the recorded signals, a method was proposed to assess the reliability of the measurements for a single passage.

A key element of the proposed algorithm is to identify the correctness of the passage of the vehicle through the WIM station. Here, the determination of the coordinates of the point of contact between the tire and the sensors is needed. This is done by analyzing signals from both the load sensors mounted perpendicular to the road axis and the piezoelectric sensors mounted obliquely to it (Fig. 3a). As the applied signal integration allows the direct determination of vehicle dynamics during the passage through the measuring station, it is not necessary to assume that the passage takes place at a constant speed in the contact location determination algorithm. The following procedure was applied to determine the passage location using integrated signals from the load sensors and the piezoelectric sensors:

a) The passing speed of each of the first two axles of the vehicle is determined using the signals from the load sensors. Then, the acceleration with which the vehicle moved when passing through the station is defined.
b) The time separation of signal amplitude maxima from the load sensors and the piezoelectric sensor excited by the load from the same vehicle wheel is calculated from the signals integrated into the measurement time window.
c) The speed of the wheel at the moment of passing through the piezoelectric sensor is determined, assuming uniformly variable movement and the acceleration calculated in step (a).
d) The calculation of the distance L covered by the vehicle wheel during movement between the load sensors and the piezoelectric sensor allows the subsequent determination of the point of contact between the tire and the piezoelectric sensor from a simple relation:

$$x = (L - \Delta)/tg\alpha \tag{1}$$

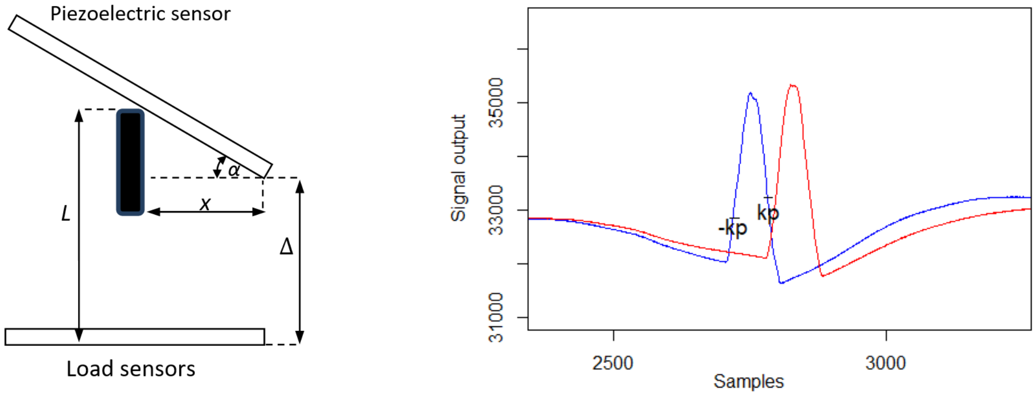
where:

Δ - minimum distance between the respective load sensors and the piezoelectric sensor,

α - the angle at which the piezoelectric sensor is installed in relation to the road axis.

The procedure for steps (b) to (d) applies to each wheel of the vehicle. A significant difference in the coordinates of the point of contact determined for the front and rear wheels of the vehicle will be visible when the trajectory of the vehicle changes.

The tire width is determined based on the signal from a piezoelectric sensor. For this purpose, the characteristic points of the signal induced by the wheel load are taken as the signal value during the observed decrease of the signal value below the reference level ($-k_p$) and during the disappearance of the signal after reaching the maximum amplitude (k_p), respectively (Fig. 3b).



a) b)

Fig. 3. a) Determination of the contact point between the tire and the sensors and b) the characteristic points used to analyze the width of the wheel

The process for determining the tire width is as follows:

a) The duration of the signal pulse Δt_p associated with the passage of a wheel through the sensor shall be determined from the moments at which the characteristic points of the signal were recorded.
b) The component of speed v_p perpendicular to the road axis of a hypothetical tire-piezoelectric sensor contact point shall be determined from the relation:

$$v_p = v_i(t)/tg\alpha \tag{2}$$

where $v_i(t)$ is the speed of a given wheel when passing through the piezoelectric sensor. Ultimately, the tire width corresponds to the distance that can be covered when moving at speed v_p over time Δt_p.

The double tire detection algorithm uses two independent approaches based on a comparison of covered distances and time intervals. Regardless of the method adopted, the elapsed time Δt_{PA} between the moments of recording the maxima of two consecutive signal amplitudes on a given piezoelectric sensor is determined in both cases (Fig. 4).

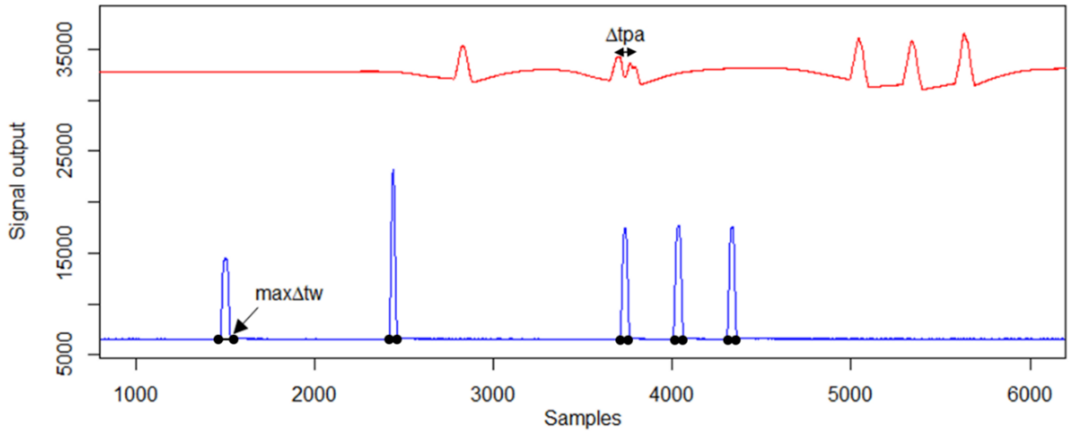


Fig. 4. An example of a signal recorded by a strain gauge sensor (blue line) and piezoelectric sensor (red line) in the case of a five-axle vehicle with a dual tire on the second axle

The following steps are followed in the method based on a comparison of covered distances:

a) The distance $S(\Delta t_{PA})$ traveled by the vehicle in time Δt_{PA} is to be determined.
b) The validity of the relation $S(\Delta t_{PA}) < S_{min}$ is checked, where S_{min} is the minimum wheelbase used for road vehicles.

If the relation is true, it is assumed that the registered signal was generated by the passage of the twin wheel. On the other hand, in the method based on comparing time intervals, once determined, the Δt_{PA} procedure is as follows:

a) The duration of the signal pulse Δt_W associated with the passage of the tested axle through the load sensors is determined, and the maximum recorded duration of the signal pulse for both load sensors is indicated.
b) The validity of the relationship $\Delta t_{PA} < \max \Delta t_W$ is checked.

If the relation is true, it is assumed that the registered signal was generated by the passage of the twin wheel.

The reliability assessment algorithm first identified the most significant factors affecting the reliability of the measurement (i.e., vehicle speed, dynamics, and trajectory during the passage), as well as external factors (road surface temperature, wind speed, and wind direction). The level of potential measurement error due to the influence of these factors is not the same. Therefore, the developed method provides an assessment of the correctness of the weighing process, both in terms of isolated factors influencing the measurement uncertainty and in a cumulative manner by determining a comprehensive impact factor. Based on the implemented algorithms for processing the integrated data and an appropriate hardware configuration (parallel measurement of external factors), the system indicates which measurements may be affected and which factors have influenced measurement uncertainty. The system controls four isolated factors: corrected speed (vehicle speed corrected for wind speed and direction), vehicle acceleration, wheel-sensor contact point (offset), and road surface temperature. The result of the measurement reliability evaluation algorithm indicates the percentage reliability index (confidence level) of the entire measurement (the comprehensive impact factor) and the values of individual impact factors (the values of such impact factors range from 0 to 1). The automated algorithm for reliability assessment has been realized using fuzzy sets based on appropriately defined membership functions. Membership functions were defined separately for each of the considered factors. Instead of discrete values limiting the acceptable range of values, the following three membership functions were introduced for each factor:

- a function for belonging to the set of parameter values regarded as normative at a given location and for a given vehicle class
- a function for belonging to a set of values lower than the aforementioned normative value
- a function for belonging to a set of values higher than the aforementioned normative value

Firstly, the algorithm performs a process of fuzzification of the recorded values by determining the degree of belonging to each of the three aforementioned sets. In the next step, the rules of inference are processed, which enable the calculation of a measure of confidence (low, medium, or high) in the reliability of the measurement due to the analyzed parameter.

The following inference rules were defined on the basis of research and testing procedures:

1. If all parameters are Normal, then the measure of confidence is High.
2. If the speed is Low/High, the measure of confidence is Medium.
3. If the acceleration is Low/High, the measure of confidence is Medium.
4. If the offset is Low/High, the measure of confidence is Low.
5. If the temperature is Low/High, the measure of confidence is Medium.
6. If the speed is Low and the acceleration is High, the measure of confidence is Low.
7. If the speed is Low and the acceleration is Low, the measure of confidence is Low.
8. If the speed is High and the acceleration is High, the measure of confidence is Low.

The processing of the adopted inference rules leads to the determination of the fuzzy set resulting from the aggregation of data representing specific confidence measures with respect to isolated factors. The next stage is the defuzzification process, which enables a single numerical value to be determined to represent the resulting sets. From the resulting value of the confidence measure, the final assessment of the reliability of the measurement carried out is performed. A reliability level of less than 50% indicates a significant probability of possible measurement error.

3. RESULTS

The system was tested at the measuring site located on the DK44 road in Mikołów – Śmiłowice (Fig. 5a).

a) b)

Fig. 5. Test site located on the DK44 road

The station was equipped with four strain gauges for wheel load measurement, two piezoelectric polymer sensors mounted at a 45° angle for tire sensor point detection, a set of induction loops, a road sensor, a weather station, and a set of cameras (Fig. 5b). The calibration tests carried out demonstrated that the system functioned in a balanced accuracy class above A(5); the mean relative error of the vehicle mass measurement did not exceed 2% [19].

A number of truck runs loaded with mass standards were carried out as part of the research work, the loads of which were verified each time by static measurements at the ITD control site. Over 360 records were recorded during the study. The runs were carried out to allow an evaluation of the influence of traffic dynamics, meteorological conditions, pavement conditions, and temperature distribution on the thickness of the mineral-asphalt package and the tire sensor contact point. As presented in other work [19], acceleration/deceleration resulted in maximum absolute gross weight error at a level of 3% and the maximum single axle load error was 16%. The position of the vehicle relative to the sensor generated errors of less than 6% for gross weight and 12% for a single axle, while the trajectory changes were 1.1% and 4.9%, respectively. In addition, the parameters of all vehicles involved in normal traffic were recorded continuously.

The system put in place for assessing the reliability of measurements works as follows: each time a passage is recorded, the system indicates the percentage reliability of the entire measurement (a comprehensive impact factor presented as a percentage value ranging from 0 to 100%), as well as the unit impact factors for the individual interference parameters (values ranging from 0 to 1, with 1 indicating the total contribution of the parameter concerning the reduction in the reliability of the measurement), as shown in Fig. 6.

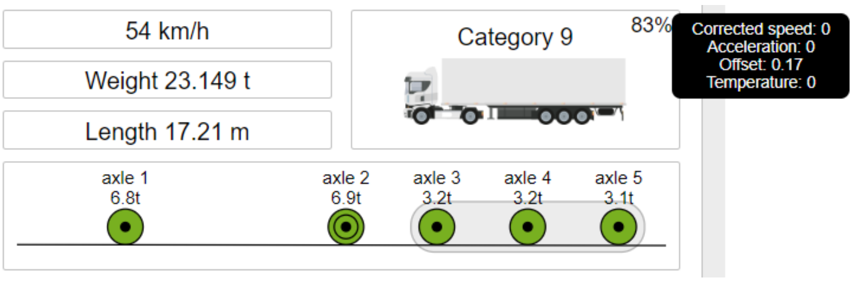


Fig. 6. Exemplary record in a graphical user interface

Table 1 shows examples of system performance for selected passages where some of the isolated parameters were outside the normative values.

Table 1

Selected examples of passages where isolated parameters were outside the normative values

			
Speed [km/h]	61	46	36
Acceleration [m/s²]	-0.12	0.02	-1.32
Offset left [cm]	77, 44, 66, 68, 66	112, 83, 105, 108, 105	112, 83, 107, 106
Offset right [cm]	46, 31, 44, 44, 44	82, 71, 80, 74, 71	76, 71, 74, 74
Temp. [°C] / WS[m/s] / WD [°]	16 / 1 / 307	11 / 6 / 108	16/ 1 /307
IF1 – speed	0	1	0
IF 2 – acceleration	0	0	1
IF 3 – offset	1	0	0
Reliability	1%	50%	50%

During the research period, the passages of 50,000 five-axle vehicles participating in normal road traffic were recorded. The percentage distribution of reliability values is shown in Fig. 7. It can be deduced from the data that 45% of the passages had factors that could interfere with correct measurement (a reliability index of less than 90%), with 16% of the recorded journeys likely to cause significant measurement errors (a reliability index of less than 50%).

Information on the width of the tires (double wheel) and the tire sensor contact point is presented in numerical form in the user interface, with dimensions given in cm. An example of the visualization of the results for a five-axle vehicle is shown in Fig. 8.

The accuracy of tire width measurements was also assessed. For this purpose, the percentage variation of the recorded results was calculated for the series of passages made with the same vehicle (Fig. 9). The largest error in determining tire width was recorded for the second axle fitted with twin wheels, with an error exceeding 20%. For the tires of other axles, the error was less than 16%.

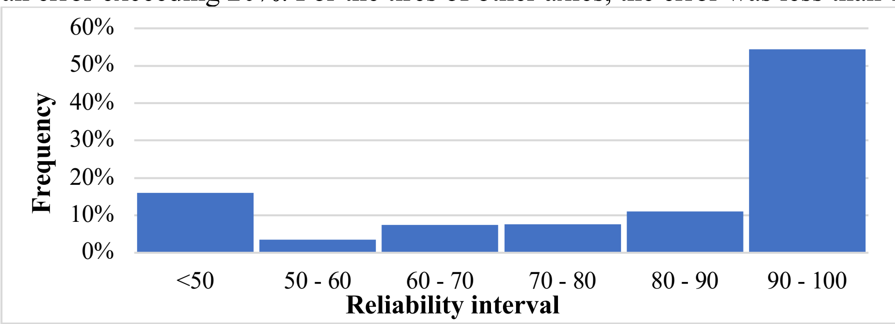


Fig. 7. Percentage distribution of the reliability result for recorded runs

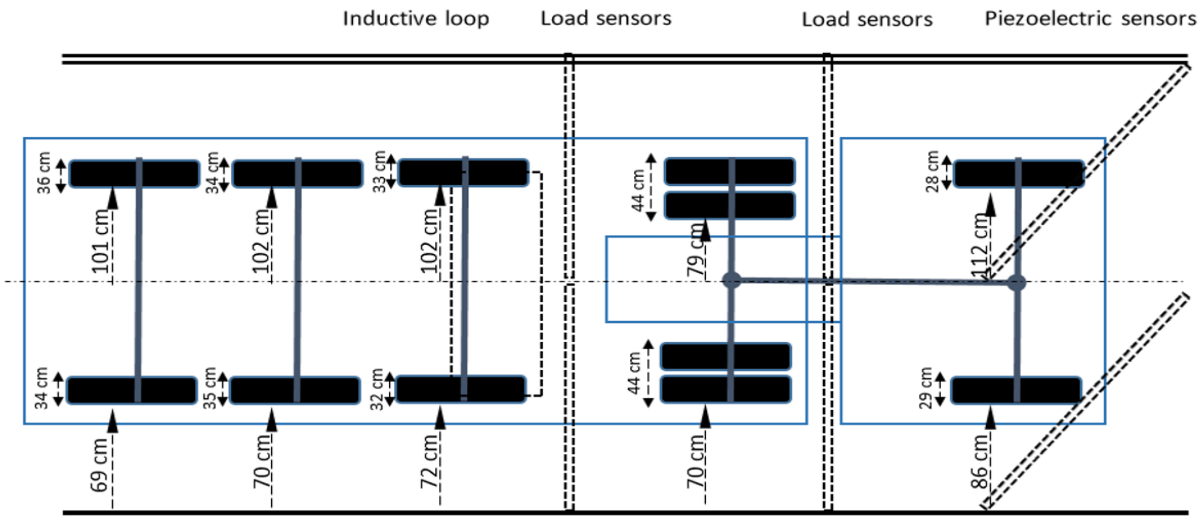


Fig. 8. An example of the visualization of the measurement results of the tire sensor contact point and tire width

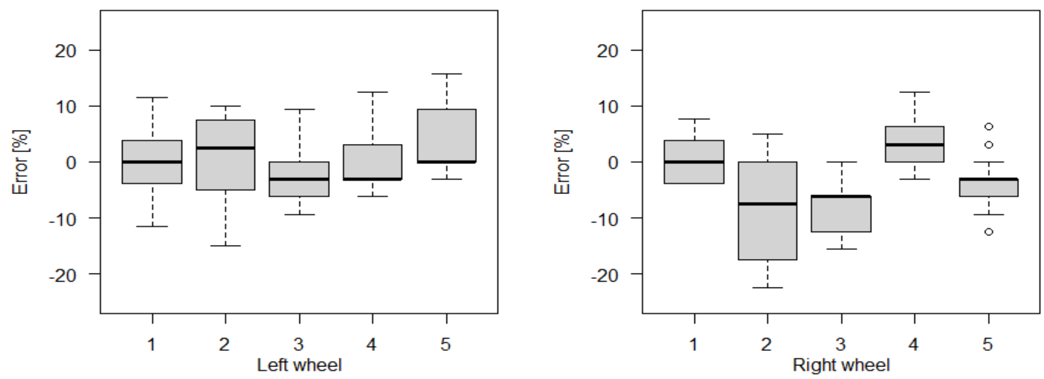


Fig. 9. The spread of tire width determination for individual wheels of a five-axle vehicle

4. CONCLUSIONS

The technological solutions and signal processing algorithms presented in this paper allowed for new functionalities for the WIM system to be proposed, including tire tread width, the designation of twin (double) wheels, and the detection of the location of the passage. The first of those functionalities is relevant from the point of view of safety and particularly the state of low wheel load. The second, which concerns twin wheels, permits the evaluation of the permissible axle load. Further, detecting the tire-sensor contact point affords the possibility of evaluating the correctness of the load measurements due to the processing characteristics of the sensors. In addition, the detection of a partial passage outside the measuring system is ensured. Such a functionality also allows trajectory changes to be tracked.

A particularly important element of the present work is the assessment of the reliability of measurements. The use of an integrated unit recording data from various measurement sensors and, thus, the collection of time-correlated information and its processing using dedicated algorithms, made it possible to assess the impact on the measurement reliability of selected parameters. These parameters are related to driving dynamics, vehicle trajectory, and ambient conditions. The evaluation method uses fuzzy sets, for which the automated algorithm for assessing measurement reliability is based on defined membership functions. The membership functions were created for each of the recorded parameters, which affected the accuracy of the measurements performed at the WIM station. The measurements taken during normal operation of the station (as well as during dedicated passages) confirmed the correct indications of the algorithm for evaluating the reliability of abnormal passages. The usefulness of the indicators related to monitoring the tire sensor contact point and the tire width estimation (double wheel detection) were also verified.

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