Scientific Journal of Silesian University of Technology. Series Transport
Zeszyty Naukowe Politechniki Śląskiej. Seria Transport

Volume 101 **2018**

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: https://doi.org/10.20858/sjsutst.2018.101.18

Journal homepage: http://sjsutst.polsl.pl

Article citation information:
Sekuła, K., Wiącek, D., Motylewski, J. In-motion rail scales as a component of the railway bridge diagnostic system. *Scientific Journal of Silesian University of Technology. Series Transport*. 2018, **101**, 203-213. ISSN: 0209-3324. DOI: https://doi.org/10.20858/sjsutst.2018.101.18.

Krzysztof SEKUŁA[1], Dariusz WIĄCEK[2], Jerzy MOTYLEWSKI[3]

IN-MOTION RAIL SCALES AS A COMPONENT OF THE RAILWAY BRIDGE DIAGNOSTIC SYSTEM

Summary: The paper presents the Adaptronica company experience in the field of the design, execution and testing of in-motion rail scales. The method of identification of loads applied in these scales is based on the measurement of rail deformations caused by passing trains. The results from experimental and simulation research on computerized railway scales are presented. The load identification algorithm and its practical implementation are shown. The implementation of the system, made on the basis of the device, is described.
Keywords: weigh in motion; railway transport; load identification; load detection procedure; structural health monitoring

1. INTRODUCTION

An important and current technical issue is the assessment of the health condition of railway bridges through the observation and registration of changes taking place in their construction. As a result of ongoing progress in the field of numerical signal analysis and

---

[1] Adaptronica Sp. z. o.o., Szpitalna 32 Street, 05-092 Łomianki, Poland. Email: ksekula@adaptronica.pl.
[2] Adaptronica Sp. z. o.o., Szpitalna 32 Street, 05-092 Łomianki, Poland. Email: dwiacek@adaptronica.pl.
[3] Adaptronica Sp. z. o.o., Szpitalna 32 Street, 05-092 Łomianki, Poland. Email: jmotyl@adaptronica.pl.

continuous improvement in the functionality of measuring devices, concepts and preliminary implementations of monitoring systems and automatic diagnostics of bridges are being developed.

An exemplary scheme of the monitoring system is shown in Figure 1. According to the cited concept, it consists of two complementary subsystems. One of them is the fault identification system in truss bridges, whose purpose is to register measurement data from sensors placed on the bridge structural elements, on the basis of which it is possible to assess the technical condition of the object on an ongoing basis. The second subsystem is the identification of the load of which the dynamic railway scale fulfils the role.

A more detailed explanation of the whole monitoring system of the railway bridge is described in [1]. This paper is focused on the load identification system in railway transport, which was designed in such a way that it can be an independent or be an element of a larger system used for monitoring railway bridges.

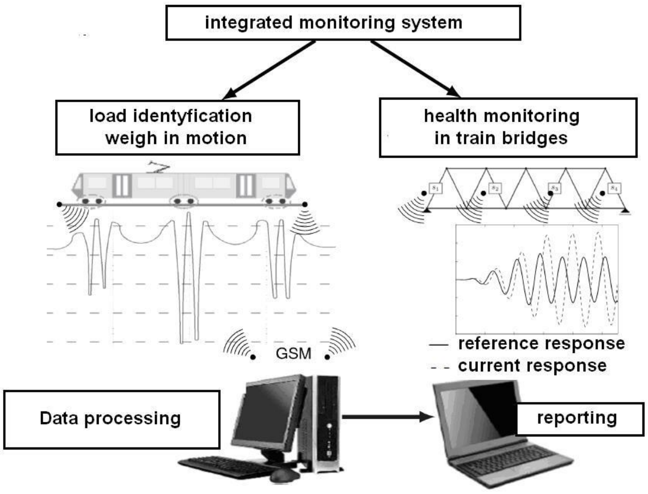


Fig. 1. General scheme of the integrated system for monitoring loads and damage in railway bridges [1]

2. OVERVIEW OF TRAIN WEIGHING SYSTEMS IN MOTION

Existing weighing systems can be categorized on the basis of different criteria, including the operation velocity range of vehicles while its weight is measured, the sensor type used and the assembling technology. Here, the authors were focused on the methods of load detector installation.

In general, two approaches to the determination of railway traffic load are possible: either using a railway car equipped with sensors [2] or performing measurements by means of external sensors fixed to the infrastructure outside the train [4]. The first method is not frequently applied and it seems to be less effective from a practical point of view. Hence, the second approach has been more deeply reviewed here. Many kinds of sensor types and installation technologies have been applied in train WIM devices. A brief overview of used technologies can be found in the papers [3,4].

The authors propose to divide the railway weigh-in-motion (R-WIM) systems on the basis of weight detector installation technology. As a consequence, the following three main categories can be introduced:

- Bridge WIM, i.e., systems that utilize the instrumented bridge measurements for traffic identification [4,5,16]
- Platform WIM, i.e., systems based on force measurement between the track and an additional solid foundation [6]
- R-WIM, i.e., systems based on the measurement of strain development in rails [3]

The device developed by the authors belongs to the third group and, as a consequence, more information related to this type of load detector will be mentioned in the next section.

2.1. Overview of rail weigh-in-motion systems

The elastic deformation of the rails is occurring when the train is passing over it. R-WIM systems operate on the basis of the strain measurements in rails. In this group of devices, two potential locations for the strain sensors are commonly used: either mounted on the rail foot [7] (see Figure 2a) or installed in the neutral axis area of the rail [8] (see Figure 2b). In the first case, the detector records the longitudinal deformation of the rail foot, which is mainly related to the bending effect of the rail. As a consequence, in this case, the sensor is most commonly installed in the midspan between the sleepers, since it provides the highest strain values. This is in contrast to the neutral axis sensor location (in the middle of the rail web), where approximately pure shear stresses are present. The bending effect is used in the device proposed by the TagMaster company in Gotcha system [13], contrary to the solution proposed by the Kistler company [14].

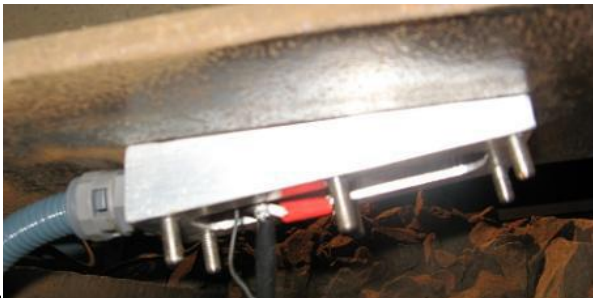
a.  b. 

Fig. 2. Two possible locations for the sensor installation:
(a) rail foot, (b) neutral axis of the rail [10]

Various types of the strain sensor are utilized in R-WIM applications. Probably, the first systems were performed on the basis of strain gauge measurements [8]; this still seems to be the most frequently used technique. However, recently, there is growing competition for strain gauges in the form of optical fibres [9,10] and piezoelectric strain sensors. In general, it is not possible to state which measurement strain sensor technique is most appropriate for R-WIM. Researchers [1,15] have proven that a similar quality of measurements can be obtained by different measurement techniques.

The important advantage of R-WIM systems is the wide velocity range of travelling trains, in which the identification of their weights is possible. Researchers have successfully applied axle load measurements for trains travelling at a velocity of 300 km/h [9]. However, in order to overcome the velocity limitations, the accuracy of results must be sacrificed. In [7], it was shown that the load identification error increases together with the velocity identification.

As the rail is in direct contact with the train wheels, the strain measurements are able to provide estimations of relatively many parameters, which is a great benefit of R-WIM systems. Quantities, such as individual wheel and axle loads, the gross weight of each railway car, the number of railway cars, total train weight, velocity, direction of movement and even the state of the wheel, e.g., polygonization, can be identified. The sensors, which are commonly installed in bough rails, allow for the estimation of the unbalanced axle load.

The important advantage of R-WIM is its relatively low cost. Very often, no additional maintenance operations, especially preparing the track (e.g., replacement of the sleepers or the installation of a solid foundation) before sensors are attached, is necessary. Another benefit is the possibility of creating an installation, even during traffic, provided that some safety conditions are respected.

It should be mentioned that the tracks are an element of the measurements system. As a consequence, the condition of tracks has an influence on the identification precision. Moreover, since the tracks' condition is not always the same, the axle load's rail strain relation is not known before sensor installation. This forces the calibration of the measurement system. The most commonly used method is to apply the train with a known weight.

Thanks to the advantages of R-WIM technologies, significant developments in this field have been recently observed. Several scientific or commercially available techniques, using various sensors or methods of installation, can be found. Generally, R-WIM systems can be distinguished according to two main categories, i.e., non-intrusive and intrusive, on the basis of the sensor assembling technique. In the first case, the sensor installation does not have any effect on the rails, as the sensor is usually glued onto them. In the intrusive system, sensor installation requires a rail intrusive operation, with the drilling of the rails being the most commonly used. The other group comprises portable systems where sensor installation is not time-consuming and the return of the rails and the whole track to the previous (i.e., pre-installation) state is easy. One example of such devices was patented by the Adaptronica company. Contrary to what is mentioned above, generally, emplaced type detectors, once they are anchored, are usually not removed and tend to be dedicated to the continuous detection of traffic information. Typically, portable systems are also non-intrusive technology because, after they are remove, there is no visible effect on the track.

3. THE CONCEPT FOR THE DEVELOPED RAIL WEIGH-IN-MOTION SYSTEM

The load identification is performed in an indirect way using the rail deformation recorded during the passage of the train. Generally, two locations for the sensor's placement are possible. As mentioned earlier, the strain sensors could be located either on the rail foot or to the rail web. The authors have chosen the former because, in this case, the sensors are less visible and partially sheltered from the rain. The strains are collected by the sensors (piezoelectric or strain gauge were used) mounted to the bottom part of the rail foot in the sleepers. The general concept of the aforementioned method is presented in Figure 3.

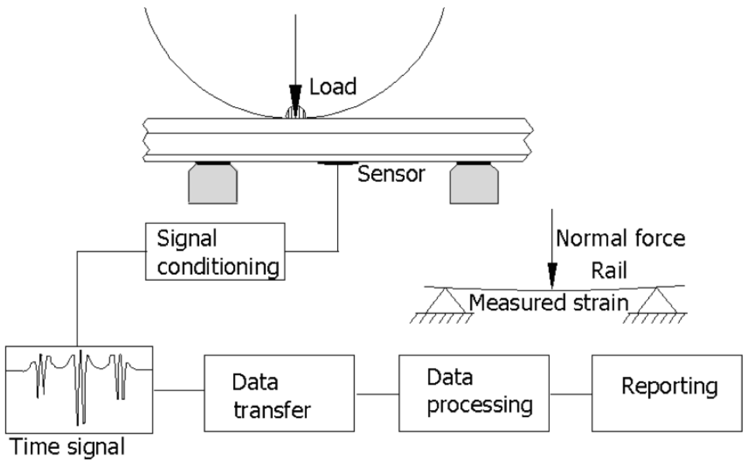


Fig. 3. General concept for the R-WIM system

4. THE LOAD IDENTIFICATION ALGORITHM

Implementing the direct measurement of loads in rail transport is difficult in practice; therefore, indirect methods are used [1]. The load identification problem belongs to the class of inverse problems presented in [11]. Generally, solving this the problem involves find a relation between the output (registered measurement signals) and input (axle load) in a given system. In order to perform this task, it would be reasonable to register the relationship, in an experimental manner, between these sizes during the work of the considered systems. This is usually difficult to carry out because, in the case of environmental enforcement (i.e., vehicle traffic), usually, only an exit (answer construction at the given load) can be measured reliably.

In the proposed R-WIM system, the pattern recognition scheme has been adopted as the method to solve the inverse problem. In the method, a Y_{DB} database, containing a mapped response design for various load variants, is used. This database can be presented as a set of values of the function described by the following relationship:

$$Y_{DB} = f\left(Q_{stat}, T, v, a_n, r_{sc} ...\right). \tag{1}$$

Formula (1) contains significant factors affecting the measurement: Q_{stat} - measured static load value, T - temperature, v - moving speed composition, a_n - number of axles in the wagon, r_{sc}- rail support condition etc.

Preparing a database involves carrying out a type of sensitivity analysis. This can be done during field research, which, for the proposed devices, was based on the crossings of railway cars with a known load distribution through the measuring zone. Another way is to perform simulation tests using a verified numerical model.

Generally, identification according to the proposed method consists of finding a vertical load, which is the same as the contact force occurring between the wheel and the Q_{id} rail. This can be performed by minimizing the difference between the currently registered Y_M and the measurement signal value similar value, as memorized in the database:

$$Q_{id} = \arg\min \left[Y_M\left(Q_{stat}, T, v, a_n, r_{sc} ...\right) - Y_{BD}\left(Q_{stat}, T, v, a_n, r_{sc} ...\right)\right]^2 . \tag{2}$$

The registration of measurement signals can be influenced by many factors. In order to simplify the identification procedure (reducing the number of variables), it is possible to use an internal calibration procedure for vehicles with a specific mass. Electric locomotives, e.g., ET-22, are ideal for this purpose as their mass is not influenced by the amount of fuel or the number of passengers. As it has been shown that the composition of a locomotive of this type is possible, the preliminary determination of the *R* relation between the value of the Y_{ML} signal is generated by the locomotive and the known static load of Q_{ML}, according to the dependence:

$$R = \frac{Y_{ML}}{Q_{ML}}. \tag{3}$$

On the basis of the currently measured strain Y_{act} and the relationship in (3), it is possible to determine the mass of other wagons using the formula in (4):

$$Q_{id} = R \cdot Y_{act}, \tag{4}$$

without the need to analyse the influence, for example, of temperature *T* and speed *v*, because this information already contains the parameter *R*, specified for the given composition under specific travel conditions. However, the formula does not consider the quantities related to some non-linear effects. In order to include the load distribution $O(a_n)$ or influence the non-linear *nli* axle load strain relation, the formula in (5) should be applied.

$$Q_{id} = R \cdot Y_{ML} \cdot O(a_n) \cdot nli \tag{5}$$

5. COMPUTER MODELLING OF RAIL-SLEPER-GROUND INTERACTION

The objective behind the preparation of a numerical model of rail-sleeper-ground interaction was to identify the rail and train configuration parameters from the load identification point of view. The factors influencing the dynamic response of the rail, e.g., the number of axles per bogie, were taken into consideration. The main objective of the analysis is to obtain the model calibration factors in order to ensure the precision of the load identification algorithm.

The railway track was modelled using the ADINA finite element package. It was assumed that the load acting on the track is distributed symmetrically; in order to reduce the computing effort, only one rail on the track has been modelled. A scheme of the model is illustrated in Figure 4.

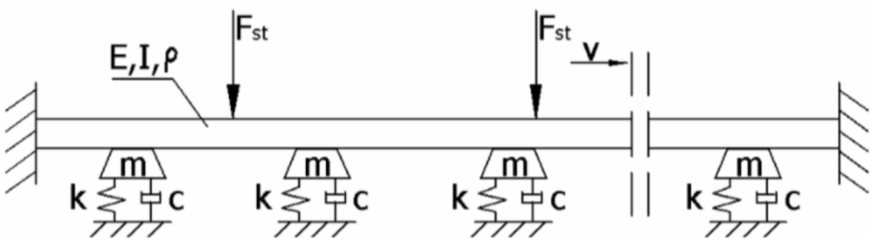


Fig. 4. Model of rail-sleeper-ground interaction [1]

The rail was modelled as a beam according to the Rayleigh-Timoshenko theory. Beam parameters, such as density *ρ*, Young modulus *E* and moment inertia *I*, were the same as for a real S60 rail. The Kelvin-Voigt model (spring and damper in parallel) was employed in order to model rail-sleeper-ground interaction. The stiffness k and damping parameters c of the model were applied on the basis of the experimental data. The load was modelled with the aid of a system of vertically concentrated forces F_{st} and moving in the horizontal direction with a constant speed v. A more detailed explanation of the presented model can be found in [1].

5.1 Verification of the numerical model

The numerical results obtained from the computer model were validated on the basis of the experimental measurements. A comparison of the results for the passage of an ET-22 locomotive is shown in Figure 5. The locomotive weighs 120 tons and is supported by two three-axle bogies; this configuration is visible in the graph.

Figure 5a represents the vertical displacement of the rail, with the experimental data acquired by using laser displacement sensors. Generally, it should be stated that the track is direct, that the measurement zone was in a bad technical condition and that the observed displacements of foundations were of a size greater than in the case of literature data [12]. The displacement sensor results were only used for model validation, while they are not applied in developed R-WIM systems.

Figure 5b presents the time history of strain in the bottom part of the rail. This quantity is directly used in the R-WIM system. The experimental data were measured by strain gauges in the half-bridge mode located in the midspan between the sleepers. Despite the fact that the load is equally distributed to the six axles, the experimental and numerical data show that the amplitude of strain corresponding to the middle axle of bogie is 25% smaller than for the outside ones. This is the result of deflecting the line of the rail.

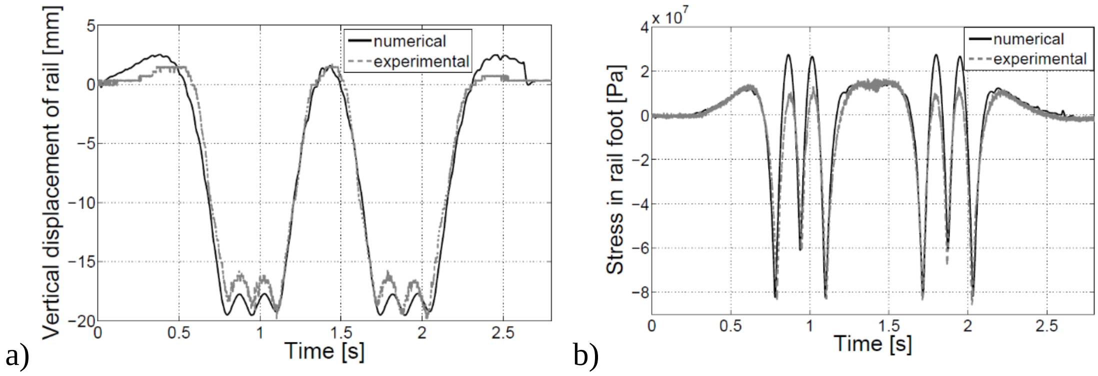


Fig. 5. Comparison of numerical and experimental results: a) vertical displacements of the rail, b) stresses in the rail foot

5.2 Analysis of the load distribution effects

Since railway cars may have a different number of axles per bogie, the analysis of load distribution effects on rail strain is considered in this section. For this purpose, numerical simulations were performed, in which the load exerted by the wagon on the rails is spread across a different number of concentrated forces. The arrangement of modelling forces on the load was selected in such a way that their distances corresponded to the spacing axes occurring in typical wagons and locomotives. Five cases of load distribution were analysed. The total load value was the same in all simulations. The obtained numerical results are shown in Figure 6. The graph presents a relative change in rail strain as a function of the axle number with the load distribution for the three-axle bogie serving as a reference.

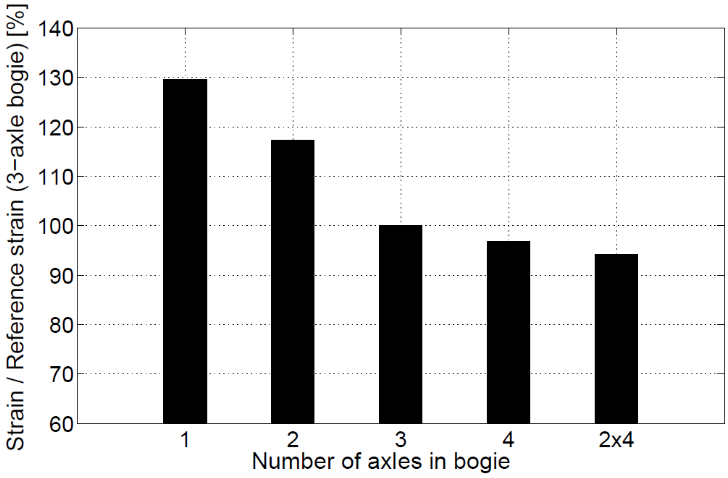


Fig. 6. The dependence of the number of axles in the bogie on the maximum relative deformation of the rail

Rail deformation is based on the quantity used for the load identification in the R-WIM system. The simulation results emphasize the significance of the number of axles in the bogie rail deformation. As a consequence, this parameter should be considered in the load identification algorithm. This factor is especially important when using the online calibration method (with the locomotive serving as a reference). The need for such a correction derives from the fact that locomotives usually run on three-axle bogies, while freight cars run on two-axle ones. Otherwise, the cars with a smaller number of axles might be identified as heavier than in reality. In the case of two-axle bogie wagons, the weight would be overestimated by 18% (see Figure 6).

6. EXPERIMENTAL VERIFICATION OF THE DEVELOPED RAIL WEIGH-IN-MOTION SYSTEM

The R-WIM system was installed in Nieporęt, near Warsaw, in the area of the bridge over the Żerański Canal. The device was equipped with four piezoelectric strain sensors located in the rail foot, according to the concept mentioned in Section 3. The two sensors were installed in bough rails at a distance of 480 mm.

The system was verified on the basis of the reference trains, which were weighed beforehand on the low-speed weighing station near Warsaw. The reference scale was produced by Schenk typ. DGW-B 8+5+5, which is characterized by the third class of accuracy; the scale interval was 50 kg.

Figure 7 illustrates the time signal collected by the piezosensor during the passage of a freight train. Each axle of the bogies running over the WIM measuring point can be recognized. The first part of the signal (approximately 15 s) corresponds to an ET-22 locomotive with two three-axle bogies. The remainder of the acquired signal is the result of the passage of 29 wagons, most of which were supported by two two-axle bogies. However, four of the last six wagons were supported with two three-axle bogies. As a consequence, three wagons were characterized by an analogical axle configuration as in the case of the locomotive. The presented train was weighed by use of the aforementioned reference scale. The measured weight of each of the wagons is depicted in the graph. The weight of the locomotive was 120 tonnes, while the wagons weighed 23.3-33.6 tonnes.

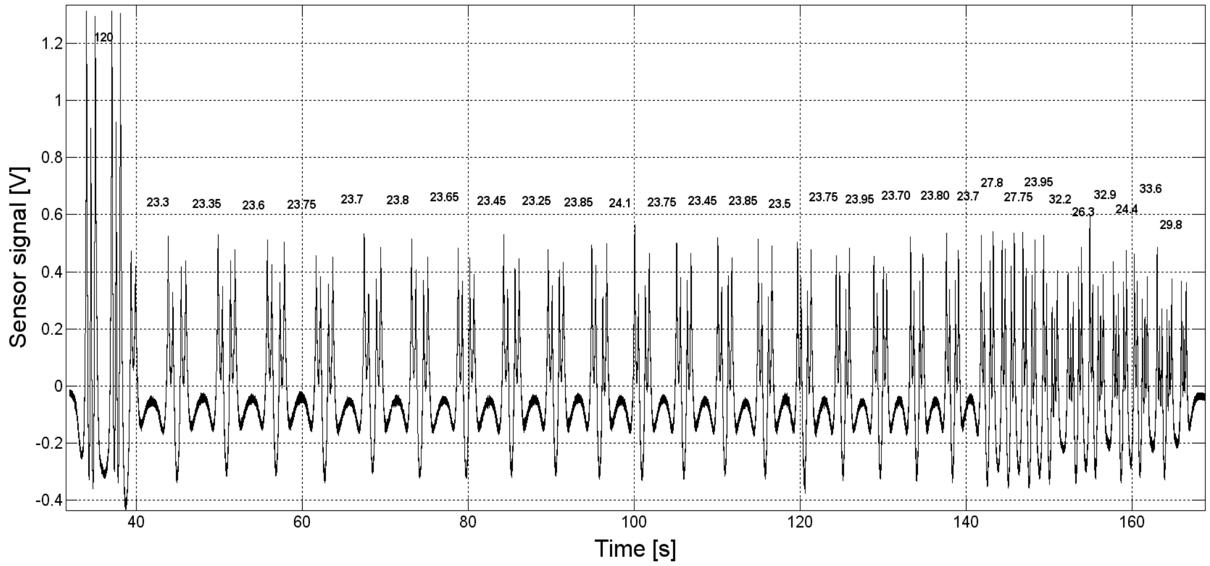


Fig. 7. Time signal from the piezosensor as a response to the passage of a freight train

In the first stage, the wagons' weight identification by using the R-WIM device was applied on the basis of the formula in (4). The mass of the locomotive was used for measurement system calibration. The signal amplitudes that related to each of the axles were the quantities used in the load identification methodology. The system identification precision is shown in Figure 8, which shows the percentage difference between the R-WIM values and the reference scale value. A significant difference in the case of the wagon supported by a two-axle bogie was noticed, while good agreement was observed in the case of the three-axle bogie. The two-axle wagon weight was overestimated by about 18±4%. These results do not contradict the computer simulation, as seen in Figure 6.

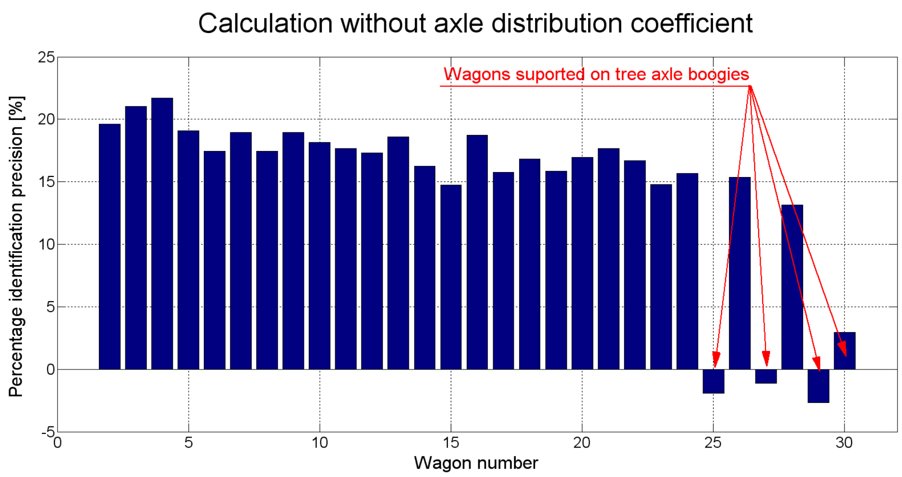


Fig. 8. Wagons' weight identification precision, based on the formula in (4)

In order to improve the identification precision, the procedure based on the formula in (5) was applied. Here, the load distribution was considered to result in a significant improvement in the identification precision, with the inaccuracy being less than 5% in that case.

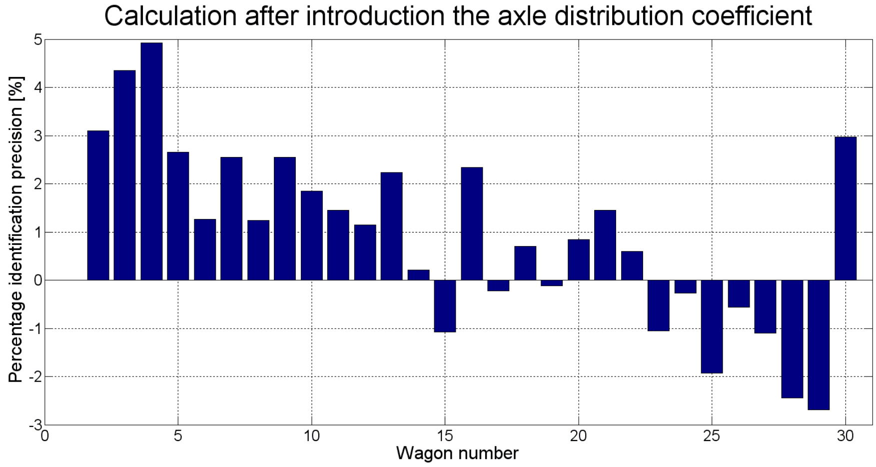


Fig. 9. Wagons' weight identification precision based on the formula in (5)

6. CONCLUSION

This paper presented an experimental and numerical analysis of a WIM system dedicated to railway transport. This device can complement the monitoring system conditions of truss railway bridges. The developed device is the R-WIM system and, as a consequence, a literature review of the relevant group scales was introduced.

A load identification method is proposed here, based on the measurement of railroad deformation caused by passing trains. Piezoelectric sensors were used to measure the deformation and, for comparative purposes, strain gauges were applied. The acquired data were used for model of rail-sleeper-ground interaction validation. The model was used in the development of a load identification algorithm. The algorithm, which is based on online calibration, makes the measurements insensitive towards environmental conditions. The numerical and experimental results have proven that the load distribution effect must be considered in the load identification algorithm.

Studies have shown that piezoelectric sensor deformation can be used to identify loads and is a good alternative to other measuring techniques.

References

1. Holnicki-Szulc Jan, Andrzej Świercz. 2014. *Monitorowanie obciążeń i stanu technicznego konstrukcji mostowych*. [In Polish: *Monitoring the Loads and Technical Conditions of Bridge Structures*.] IPPT Reports on Fundamental Technological Research. ISBN 978-83-89687-88-3.
2. Uhl Tadeusz. 2007. "The Inverse Identification Problem and Its Technical Application". *Archive Applied Mechanics* 77: 325-337. DOI: 10.1007/s00419-006-0086-9.
3. Meli E., L. Pugi. 2013. "Preliminary Development, Simulation and Validation of a Weigh in Motion System for Railway Vehicles". *Meccanica* 48(10): 2541-2565. DOI: 10.1007/s11012-013-9769-9.
4. Axel Liljencrantz. 2007. *Monitoring Railway Traffic Loads Using Bridge Weight-in-motion*. PhD thesis. Stockholm, Sweden: Division of Structural Design and Bridges, Royal Institute of Technology.

5. Žnidarič Aleš, Jan Kalin, Maja Kreslin, Peter Favai, Przemysław Kolakowski. 2016. "Railway Bridge Weigh-in-motion System". *Transportation Research Procedia* 14: 4010-4019. Available at: https://doi.org/10.1016/j.trpro.2016.05.498.
6. Denis M. Senyanskiy. 2003. "Problem of Increasing the Accuracy of Railway Carriages Weighing in Motion". *XVII IMEKO World Congress*. Available at: http://www.imeko.org/publications/wc-2003/PWC-2003-TC3-027.pdf.
7. Ignesti Mirko, Alice Innocenti, Enrico Meli, Luca Pugi, Andrea Rind. 2013. "Development and Validation of Innovative Weighing in Motion Systems". *Chemical Engineering Transactions* 33. DOI: 10.3303/CET1333128.
8. James G. 2003. *Analysis of Traffic Load Effects on Railway Bridges*. PhD thesis. Stockholm, Sweden: Structural Engineering Division Royal Institute of Technology.
9. Massimo Leonardo Filograno, Pedro Corredera Guillén, Alberto Rodríguez-Barrios, Sonia Martín-López, Miguel Rodríguez-Plaza, Álvaro Andrés-Alguacil, Miguel González-Herráez. 2012. "Real Time Monitoring of Railway Traffic Using Fiber Bragg Grating Sensors". *IEEE Sensors Journal* 12(1): 85-92.
10. Lai C.C., Jacob C.P. Kam, David C.C. Leung, Tony K.Y. Lee, Aiken Y.M. Tam, S.L. Ho, H.Y. Tam, Michael S.Y. Liu. 2012. "Development of a Fiber-optic Sensing System for Train Vibration and Train Weight Measurements in Hong Kong". *Journal of Sensors*. Article ID 365165. DOI: 10.1155/2012/365165.
11. Inoue H., J.J. Harrigan, S.R. Reid. 2001. "Review of Inverse Analysis for Indirect Measurement of Impact Force". *Applied Mechanics Reviews* 54(6): 503-524. DOI:10.1115/1.1420194.
12. Nielsen J., J. Oscarsson. 2004. "Simulation of Dynamic Train-track Interaction with State-dependent Track Properties". *Journal of Sound and Vibration* 275: 515-532. Available at: https://doi.org/10.1016/j.jsv.2003.06.033.
13. TagMaster. 2016. *Wheel Flat Detection and Axle Load Measurement. Technical Report*. Available at: https://tagmasterna.com/wp-content/uploads/2016/05/Gotcha.pdf.
14. Cornu D. 2008. *Weight-in-motion Unique Quartz Sensor Technology: Now Also for Railways. Technical Report*. Winterthur: Kistler. Available at: http://www.bleif.com.ar/assets/img/productos/files/Trasductores-de-Presion/Weigh-In-Motion-Railways.pdf.
15. Ostasevicius V., I. Milasauskaite, R. Dauksevicius, V. Baltrušaitis, V. Grigaliūnas, I. Prosyčevas. 2010. "Experimental characterization of material structure of piezoelectric PVDF polimer". *Mechanika* 6: 78-82.
16. Moravcik M., M. Moravcik. 2017. "Resonance vibration of railway bridges subjected to passing vehicles". *Komunikacie* 3: 96-102.

Received 04.08.2018; accepted in revised form 01.11.2018