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Transportation Research Procedia 14 (2016) 4010 – 4019

Transportation Research Procedia

www.elsevier.com/locate/procedia

6th Transport Research Arena April 18-21, 2016

Railway bridge Weigh-in-Motion system

Aleš Žnidarič [a,*], Jan Kalin [a], Maja Kreslin [a], Peter Favai [b], Przemyslaw Kolakowski [c]

[a]*Slovenian National Building and Civil Engineering Institute, Dimičeva 12, 1000 Ljubljana, Slovenia*
[b]*Cestel d.o.o., Špruha 32, 1236 Trzin, Slovenia*
[c]*Adaptronica ZOO SP, Ul. Szpitalna 32, 15 05 092 Lomianki, Poland*

Abstract

The paper provides an overview of the development of a railway bridge weigh-in-motion (B-WIM) system, one of the first of its kind for weighing trains in motion. A steel truss bridge in Poland was used for testing the system. Four trains which passed over the bridge were weighed in a rail yard in Warsaw. The conventional road B-WIM system was adapted to calculate the weights of the train carriages using the measured response from the test bridge and the accuracy of the system was assessed. Initial result showed that weights of one of the four trains of known weight were predicted very accurately, but accuracy of the other three trains was poor, with calculated carriage weights deviating by as much as 30% from their actual values. An in-depth analysis showed that these trains were changing velocity as they traversed the bridge and that the large errors were directly correlated to this changing velocity. The standard B-WIM algorithm, which assumed a constant velocity during the passage of a vehicle or train, was adjusted to allow for the effect of this changing velocity. The results improved dramatically, with the vast majority of the calculated wagon weights falling within 5% of their actual values. Further developments tailored the B-WIM algorithm for weighing trains, including the system interface that employs graphics of locomotives and wagons. The development of the railway B-WIM has been a success and has demonstrated that calculations of train weights using instrumented bridges can be efficiently performed.

Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)

Keywords: accuracy; B-WIM; measurement error; train; Weigh-in-Motion

* Corresponding author. Tel.: +3861 2804 207; fax: +3861 2804 484.
E-mail address: ales.znidaric@zag.si

2352-1465
Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)
doi:10.1016/j.trpro.2016.05.498

1. Introduction

This paper discusses results obtained in a 2-year research project BridgeMon which was funded under the *Research for the Benefit of SMEs* scheme of the 7th Framework Programme of the European Commission. The two main objectives of the project were to enhance accuracy and performance of SiWIM® bridge weigh-in-motion system manufactured by a SME partner in the project, and to work on tools for structural health monitoring, particularly bridges. This paper deals with the extensions of bridge weigh-in-motion (B-WIM) technology to railway bridges which was first researched around ten year ago, see (Liljencrantz, Karoumi, & Olofsson, 2005) and (James, 2005), but has never reached the implementation phase.

2. Bridge Weigh-in-Motion background

B-WIM systems use existing bridges as scales to weigh vehicles as they traverse the structure at full speeds (COST 323, 2002). A number of strain sensors are placed across the width of the structure, typically around the mid--span section where responses are the highest (Žnidarič, Lavrič, Kalin, & Kulauzović, 2011). Sensor readings from several sensors across the width of the bridge are added to compensate for small variations in lateral position of the vehicle. B-WIM systems have a number of specific advantages over the pavement WIM systems. Among others, the weighing platform (the bridge) is much longer than of any other technology, installations are completely portable and can be installed on the bottom side of bridges without interrupting the traffic (WAVE, 2001).

The basic principle of a B-WIM algorithm (Moses, 1979) is to calculate the axle loads by minimising the difference between the measured response $g(t)$ and the theoretical fitted response $f(t) = A_1I(t\text{-}t_1) + A_2I(t\text{-}t_2) + \dots$, where A_i is the i^{th} axle load and t_i is the time of arrival of the i^{th} axle at the coordinate system origin – the row of weighing sensors. The function $I(t)$ is known as the influence line (IL) and describes the response of the bridge at the sensor location to a passage of unit weight. The objective function depends linearly on the unknowns; the Singular Value Decomposition (Press, Teukolsky, Vetterling, & Flannery, 2007) is used to find the axle loads.

2.1. Calculation of vehicle velocity

Calculating the vehicle velocity requires two strain sensors which are mounted at different longitudinal locations on the bridge. Correlation between the two signals defines the time shift of one signal relative to the other at which the match between the signals is the best. The location of the peak in the correlation is used to determine the time shift which, with the known distance between the SMPs defines the speed of the vehicle.

2.2. Axle Detection

Axles are detected from sensors that are located where as sharp axle peaks as possible are detected. This can be either one of the speed or weighing sensors or a separate sensor used exclusively for this purpose.

Once the sensor has been selected, its signal is smoothed by performing two centred moving averages with different averaging lengths. The shorter one smooths out the high-frequency noise and the longer one determines the general shape of the response. The two of them are combined to amplify the axle peaks. These are defined as passage times of axles if they exceed a predefined threshold level.

Once the speed of the vehicle and the passage times of individual axles have been obtained, it is a simple matter to calculate the axle spacings by multiplying the speed of the train by the differences between the passage times of pairs of consecutive axles.

2.3. Influence Lines

Influence lines (IL) are the key structural functions that define how structural elements respond to the loading crossing the bridge (OBrien, et al., 2008). Research and many years of experience have shown that the influence lines for B-WIM must be calculated by using measurements (Žnidarič, et al., 2002) as theoretical influence lines provide unrealistic description of actual bridge behaviour.

Using a non-linear minimisation procedure the SiWIM® system calculates the influence lines from random vehicles, without knowing the actual axle loads and axle spacings (Žnidarič, et al., 2011). A few tens of such evaluations are typically averaged into the influence lines that are used for further calculations. ILs are modelled with cubic splines for which some of the points are fixed (supports) and locations of some are “forced” to specify the peak of the IL. Since the system no longer depends linearly on the unknowns, the calculation method is inherently non-linear. In the Moses’ algorithm, the unknowns are only the axle loads. In the IL calculation algorithm, the IL itself is also an unknown. SiWIM® uses Powell’s minimisation (Press, Teukolsky, Vetterling, & Flannery, 2007) to solve the problem.

Figure 1 shows the result of such a calculation as presented by the SiWIM® software. The light blue trace, mostly hidden behind the magenta trace, is the measured response. The magenta trace is the fitted function after the axle loads and the IL have both been calculated. The four lower traces are the influence lines multiplied by the individual axle loads of the 4-axle passenger train that are summed into the purple response curve. The bold and the standard circles indicate the fixed and the variable points of the cubic spline, respectively.

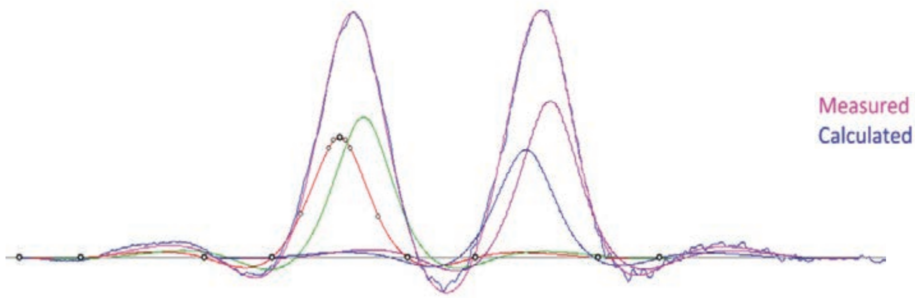

Fig. 1. Calculated influenced lines and comparison of measured and modelled strain signals.

The other known method uses vehicles of known axle loads and spacings and an inverse Moses algorithm to derive the experimental influence lines (OBrien, et al., 2006). This method is more straightforward but requires vehicles of known weight, which are not always available at the time of setting-up of the B-WIM system.

3. Railway bridge Weigh-in-Motion system

3.1. Nieporęt Railway Bridge

The objective of BridgeMon project was to try to extend the well-established road applications of B-WIM system to railways. As this work was done primarily for the Polish SME Adaptronica, a typical Polish truss bridge was chosen for testing of the Rail B-WIM software. It is located in Nieporęt, near Warsaw, and is among over one thousand similar bridges in Poland (Kolakowski, Sala, Pawlowski, Swiercz, & Sekula, 2011). Its steel truss spans over 40 m and consists of five 8 m long bays. The height of the truss is also 8 m. Figure 2 shows an elevation (a) of the Nieporęt Bridge and a view from underneath the bridge (b). A more detailed description of the model can be found in (Cantero, et al., 2013).

3.2. Field testing

Field testing with the SiWIM® hardware and software was performed between 20th and 25th of May, 2013. On the first two days, the sensors and the system were installed. On the 22nd of May the first of four reference trains, which were weighed beforehand on the low-speed weigh-in-motion weighing station near Warsaw, passed the bridge. Signals from three other pre-weighed reference trains were captured on the 24th and on the 25th of May. The static train weights of all four trains were provided by Adaptronica after the field testing was complete. In addition, responses of 23 other passenger and 19 other cargo trains were captured.

a) b)

Fig. 2. Nieporęt Bridge: side view (a) and view from underneath (b).

3.3. Sensor locations

Strain sensors were installed on the longitudinal trusses, on stringers and on cross beams. To avoid welding or drilling, steel mounting plates were applied as the interface. They were glued to the structure with epoxy and, after hardening, the strain sensors were fastened with nuts, as shown in Figure 1, left. In addition, a few extra strain gauges were glued directly on the steel structure.

One of the main characteristics of a B-WIM installation is that any intervention from the track side can be avoided, which is an important advantage from safety and maintenance points of view. Therefore, it was envisaged that the sensors on the beams, right beside the sleepers, would be used for axle detection. However, captured signals from the passing trains revealed that the axle loads distributed over the entire rail-sleeper-bridge system did not result in sharp peaks of individual axles in a bogie (double or triple axle). To overcome this issue and to allow accurate axle detection, the sensors were moved from their initial locations to the bottom flange of the rail between two sleepers, as shown in Figure 3, right. These sensors could have potentially been used also for weighing, as with some other existing railway WIM systems, yet this would not be in line with the main objective of the project.

Fig. 3. Strain sensors attached over glued mounting plates.

3.4. Preliminary railway B-WIM results

The software had to be adapted to allow working with trains. The conventional road system constantly monitors the measured strains. Then it forms the so-called events that store all measured strains that exceed a predefined threshold. This captures all activities – vehicle(s) on the bridge – that need to be processed. In later stages, the software for each individual event:

- calculates average speed of the event,
- defines axles,
- merges axles into vehicles, based on the classification table that defines all expected vehicle configurations,
- performs weighing,
- displays the results.

The fundamental difference that prevented the road SiWIM® system from working for trains was in stage (c). As trains come with indefinite combination of wagons, these cannot be all stored in a classification table. Consequently, a new module was written that divides the train into individual locomotives and wagons that are calculated individually.

After setting parameters for data acquisition, the influence lines were calculated for the sensors used for weighing. The short passenger trains were used to derive the influence line, as shown in Figure 1.

Figure 4 presents the response of the first reference train. It can be seen (see detail in Figure 5) that the calibrated system provided almost a perfect match between the measured (blue) and calculated (purple) bridge responses. This is an important but not the only condition for getting accurate results. It is however a guarantee that physical measurements were performed in the best possible way.

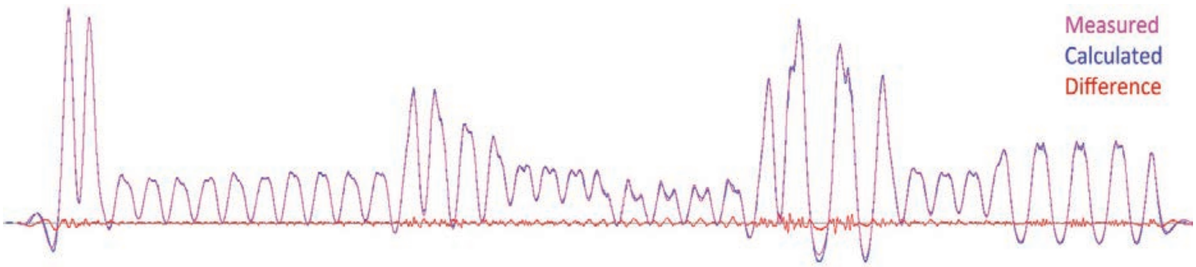

Fig. 4. Measured and calculated signals of all four reference trains.

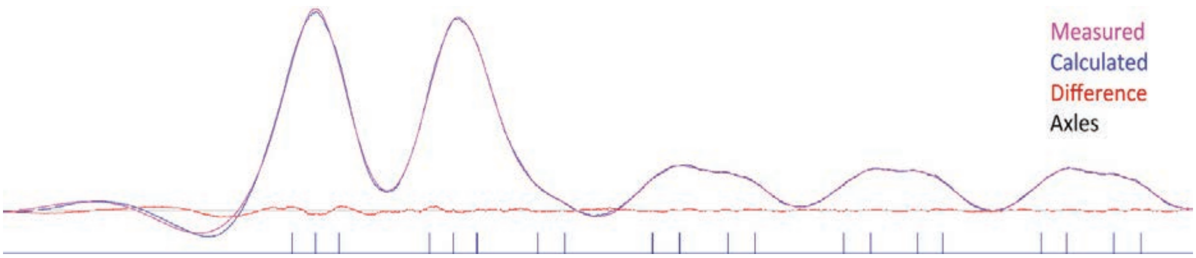

Fig. 5. Measured and calculated signals of train 1 – detail of locomotive and first three and a half wagons.

3.5. Low-speed weighing of trains

To verify the results of the measuring system, four cargo trains were weighed on a low-speed weigh-in-motion scale for trains (Figure 6) that is installed in a railyard in Warsaw and weighs trains at speeds of up to 5 km/h. Due to the limitations of this device only results for the gross weights of wagons, without individual axle loads, were obtained and could have been compared with the railway SiWIM® results.

4. B-WIM results

The in-motion results were calculated using the standard road B-WIM algorithm, and as discussed later, were further improved with modifications, which made it more suitable for weighing trains. All four trains were calibrated with the electric locomotives ET22 (Figure 7) which has a standard and more or less constant total weight

Fig. 6. Low-speed weigh-in-motion system for train weighing (left) and one of the calibration trains on it.

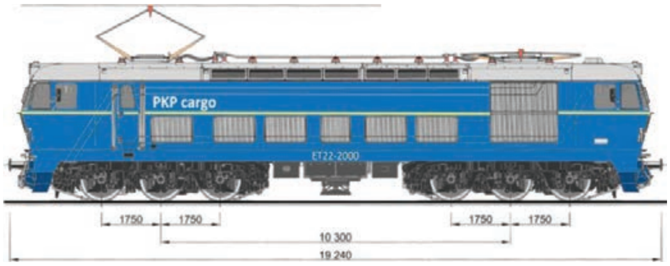

Fig. 7. ET22 Locomotive configuration (www.locomotives.com.pl).

of 6 × 20 = 120 tonnes. The thicker solid lines in Figure 8 present, for all four reference trains, the error of SiWIM® results for individual wagons. The following apparent conclusions were made:

1. While the results of train 2 were extremely good, with the peak-to-peak error just slightly over 2% and the standard deviation of error only 0.56°%, the results of other three trains were disappointing, with errors exceeding 30%.
2. A close look at the results and a detailed study of each individual wagon showed that the most apparent source of errors was the fact that the software assumed constant velocity of all vehicles in an event. On the road this provided sufficiently accurate evaluations for single vehicles in an event and acceptably low errors of several vehicles in a single event, even if they did not drive at the same speed.
3. In the case of Nieporęt Bridge, the varying train speed influenced enormously the results. The 20 km/h speed limit for trains crossing the bridge caused significant variation of speed during train crossings. This was exaggerated for longer trains, some of which exceeded 500 m in length. As the variation in measured speed in the worst case (train 4) surpassed 40%, the assumption of constant velocity clearly ceased to be valid.

4.1. Effect of non-constant velocity of trains

The effect of train speed on the accuracy of results was studied in detail. The software could not evaluate velocities of individual cars, but provided axle spacings of individual wagons. This information was compared to the constant axle spacings of the measured types of wagon, to obtain variations of velocity of individual wagons. As the WIM axle loads are directly related to the vehicle velocity, the variations of wagon velocities (dashed lines in Figure 8) were compared with the errors of the corresponding SiWIM® results of wagons. Correlation between GVW and velocity was self-explanatory.

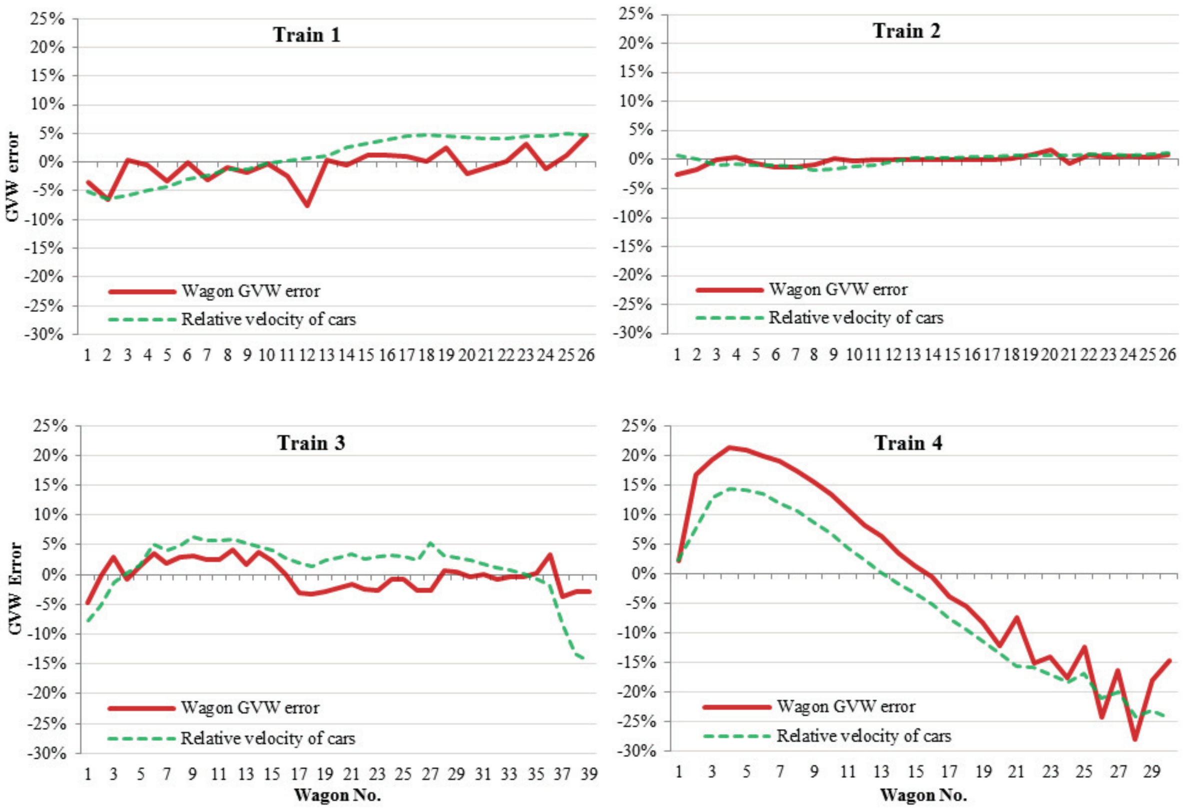

Fig. 8. Error in gross weights and variation of velocity of individual wagons – trains 1 to 4.

4.2. The solution

Clearly, the assumption of constant velocity of the train was not appropriate for railway B-WIM algorithm, especially if the speed is limited at or near the bridge, as was the case in Nieporęt. This resulted in late braking and early acceleration, which was observed for 3 of 4 trains that were analysed. The solution for this problem was to modify the algorithm and replace constant velocity with individual wagon velocities.

In the standard processing chain, the velocity is calculated as the first step after splitting the signals into events. The events on road bridges contain a number of vehicles, but on railway bridges the whole train is treated as one event. The per-lane velocities for the event, in this case the average velocity of the train, are calculated using cross--correlation of the entire signals from pairs of speed measurement points (SMPs). The next two steps are:

- identification of axles and
- joining of axles into vehicles.

After vehicles have been identified, the axle loads are evaluated and the raw results multiplied with calibration factor to obtain the final results.

In the modified algorithm, an additional step has been inserted which calculates the per-carriage speed using correlation of only those parts of the signals that contain information for the passage of a single locomotive or wagon.

The improvement in accuracy for the four reference trains has been significant. Figure 9 displays the errors in the predicted wagon weights for each of the trains when considering (i) the average velocity of the train – the entire loading event (solid lines) or different velocities for each of the wagons (dashed lines).

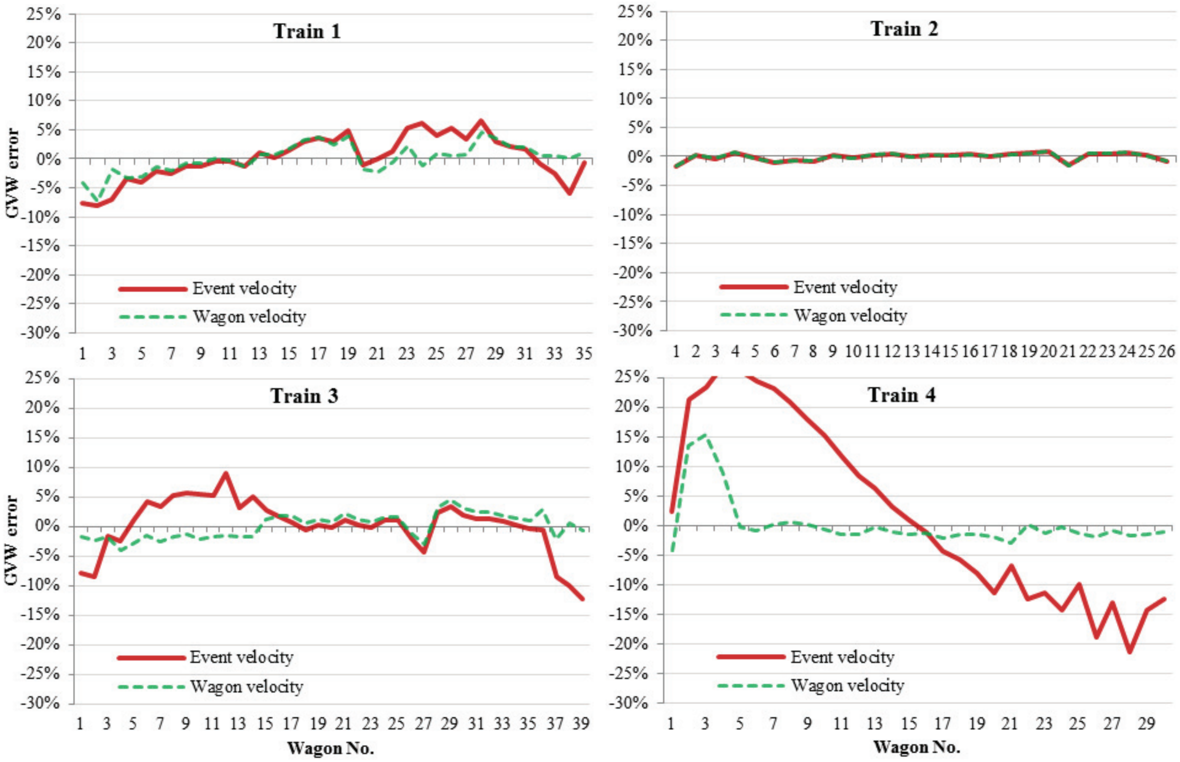

Fig. 9. Error in gross weights of velocity of individual wagons for event and wagon velocities – trains 1 to 4.

It shall be noted that the fourth reference train still exhibits large errors for the first four carriages. This resulted from a heavy rain just before the passage of this train. It is suspected that water temporarily shortened the axle detection strain gauge, which, for the 3-day measurement, was not fully protected against environmental effects. Consequently, the noisy speed measurement signal (the shaded area in Figure 10) resulted in erroneous velocities for these wagons. Such errors may easily be avoided by protecting the sensors against environmental effects.

4.3. Additional modifications

In order to further improve the velocity calculation, another modification to the algorithm has been implemented and partially tested. The adaptation is based on the fact that axle spacings for locomotives and wagons are well defined.

Once vehicles have been identified and their individual speeds calculated, the axle spacings were compared against a specification of known axle spacings provided by Polish Railways. The nearest match was found and if the differences of all axle spacings were within the predefined tolerances (typically 0.2 m), it was assumed that a standard locomotive or wagon was found and axle spacings from the specifications were applied. First, the speed was adjusted so that the total measured length of the vehicle matched the sum of all axle spacings from the specification. Then the axle spacings themselves were adjusted.

Simulations have shown some modest improvements of accuracy. One obstacle was that not all axle spacing configurations captured on site were included in the specification provided. For the purposes of testing, the reference lengths were calculated from the average measured axle spacings of similar wagons.

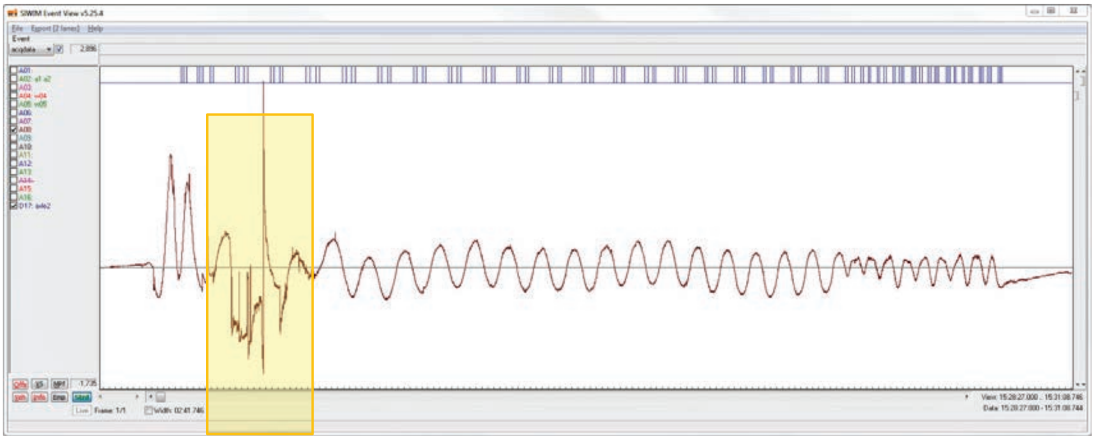

Fig. 10. Error in velocity detection sensor (shaded area).

Finally, the software itself was adjusted for railways. A number of extra parameters had to be included to facilitate the new features described above. These are stored in several additional configuration files. Then, a new classification table was setup that defines characteristics of most locomotives and carriages that circulate on Polish railways. As a final point, the software interface was adapted to display locomotives and wagons instead of heavy road vehicles.

5. Accuracy of railway B-WIM results

Table 1 summarises the results obtained with traditional road B-WIM system and those obtained with all railway--related improvements described above. The columns display the means and standard deviations of errors of all four reference trains obtained by conventional and modified B-WIM algorithms. Clearly, improvements were substantial and have potential for further advancements when the requests by a particular railway operator are advised.

Table 1. Strain gauges corresponding to the sensor locations.

Train	Original		Modified	
	Mean error	COV of errors	Mean error	COV of errors
1	3.0%	3.6%	2.3%	2.8%
2	0.5%	0.7%	0.5%	0.7%
3	3.3%	4.6%	1.2%	1.6%
4	13.3%	15.4%	2.2%	3.2%

6. Conclusions

The BridgeMon FP7 project investigated two issues related to railway bridges: development of a railway B-WIM system to collect accurate in-motion traffic loading information and a structural health monitoring (SHM) system. It was suggested that a combined B-WIM and SHM system would be a very useful tool for bridge owners that would help them keeping the aging bridge stock at an acceptable level of reliability. A railway bridge in Nieporęt in Poland was selected for testing the B-WIM and SHM concepts.

For the railway B-WIM part of the research, a finite element model of the bridge was developed. Then the bridge was instrumented with strain transducers and the SiWIM® bridge WIM system. This was until before the BridgeMon project applied exclusively on road bridges and had to be modified for weighing of the trains.

During a 3-day testing period forty-six trains were captured. Four of them have beforehand passed a low-speed WIM station in Warsaw and, knowing the actual weight of these four trains, allowed testing of accuracy of the

B-WIM system. Only the gross weights of the wagons were used for assessment, as the axle loads were not recorded during the low-speed WIM measurements.

Initial results demonstrated that one of the four trains of known weight, the only train which crossed the bridge with constant speed, was weighed very accurately, with all wagon weights errors falling within the -0.9% to 1.6% interval. This suggests that accuracy potentials are much higher than it could have been shown on the Nieporęt Bridge. However, accuracy of the other trains was disappointing with calculated wagon weights deviating by as much as 30% from their reference values. An in-depth analysis revealed that these trains were changing speed as they traversed the bridge and that the large errors were directly correlated to the changing velocity. The standard B-WIM algorithm, which assumed a constant velocity during the passage of a vehicle or train, was adapted accordingly. Results improved dramatically, with 75% of all calculated wagon weights falling within ±2% and 97% of them falling within ±5% of their actual values. Further developments tailored the B-WIM algorithm for weighing trains, including the system interface that employs graphics of locomotives and wagons.

The development of railway B-WIM has been a success as it had shown its clear potential for railway applications. The remaining challenges include a) finding better ways for axle detection that would avoid any sensors on the track side, which is the key B-WIM advantage from safety and maintenance points of view, b) better integration of known vehicle parameters, particularly the known locomotive weights and complete table of carriage axle spacings and c) testing of the system on other type of bridges; a steel truss is a common but complicated structure to apply B-WIM on. Some solutions have already been investigated and proposed in the Bridgemon project reports (Ni Choine, Žnidarič, Corbally, & Kalin, 2014). Last but not least, combination of results obtained from the rail and from the bridge may further increase accuracy of railway WIM system results in general.

Acknowledgment

The authors would like to express their gratitude for the support received from the 7th European Framework Project BridgeMon (2012-14) towards this investigation.

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