BridgeMon: Improved Monitoring Techniques for Bridges

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ABSTRACT: Many bridges in the world's transport infrastructure are old and have deteriorated over time. The solution to this problem is to either repair or replace a bridge or to establish its safety and maintain it in service. It is generally very costly to repair or replace a bridge. With reduced maintenance budgets there is an increasing interest in maintaining these old bridges in service by using probabilistic methods to prove that they are safe. Bridge safety is assessed based on (i) the loading which it will experience in service and (ii) the resistance of the structure. Improved knowledge of loading and resistance allows a more accurate assessment of whether a bridge is safe to remain in service without the requirement for expensive repair or replacement strategies. BridgeMon is an EU-FP7 funded project which aims to improve current monitoring techniques for road and rail bridges. This will be done by developing improved methods of evaluating traffic loading on bridges and carrying out Structural Health Monitoring (SHM) to identify damage and assess their remaining resistance. Bridge Weigh-in-Motion (B-WIM) refers to the technique of using the measured response of a bridge to calculate the vehicle loads crossing it and is a useful tool in monitoring traffic loading on bridges. BridgeMon will improve the accuracy of current B-WIM technologies and develop the first B-WIM system for railways. It is also developing the concept of virtual monitoring, whereby sensors are used to calculate vehicle weights which are then used to calculate stress histories throughout the bridge. Results of testing of a rail B-WIM system on a bridge in Poland are presented. Results show that the system is capable of accurately calculating train weights.

KEY WORDS: Bridge; Weigh-in-Motion; B-WIM; WIM; Structural Health Monitoring; SHM; Railway; Train; Loading.

1 INTRODUCTION

Major transport networks rely heavily on the safety and serviceability of bridges located on these routes. Failure of a bridge can have devastating effects from both an economic perspective and regarding loss of human life. It is therefore imperative that the safety of these bridges is ensured. A vast number of bridges which are critical to the efficiency of road and rail transport networks are old and have deteriorated since their construction. In many cases these bridges have reached their design lives and, as such, a decision must be made as to whether the bridge needs to be repaired or replaced, or whether it is safe to retain in service.

With limited maintenance budgets available, replacing old bridges which have exceeded their design lives is an expensive and time-consuming strategy. Many bridges have been designed for loading scenarios far in excess of any which have been experienced during the working life of the structure. As such, these bridges may exhibit the necessary capacity to remain in service without the requirement for expensive repairs or replacement.

In order for these bridges to remain in service it must be proven that it is safe to retain them, i.e. that their probability of failure is below an acceptable level. Bridge safety can be evaluated by comparing the maximum loading that is expected to the resistance of the structure to that loading. Therefore, an accurate safety assessment requires detailed knowledge of the loading on the bridge along with its resistance.

The BridgeMon project aims to improve current bridge monitoring techniques in order to allow accurate evaluation of both loading and resistance characteristics for road and rail bridges.

2 OBJECTIVES OF BRIDGEMON

BridgeMon (**Bridge** Safety **Mon**itoring) is an EU FP7 funded project which has been supported under the 'Research for the Benefit of SMEs' programme. The project focuses on developing new monitoring techniques for the evaluation of bridge loading and resistance. Applications for both road and rail bridges are considered within BridgeMon.

2.1 Bridge Weigh-in-Motion

Weigh-in-Motion (WIM) is a term used to collectively refer to the various technologies which have been developed to allow the weighing of vehicles which are travelling at full traffic speed. Conventional WIM systems are pavement based, mostly involving pressure sensors embedded in the road pavement. B-WIM refers to an alternative WIM approach whereby the structural response of a bridge is measured during the passage of a vehicle and is then used to calculate the weight of that vehicle and its axles. B-WIM has the advantage of being portable, as well as providing direct information on the structural behaviour of the bridge being used. The ability to weigh vehicles without having to stop them allows for large scale collection of traffic loading data for roads and bridges. Figure 1 illustrates the B-WIM concept.

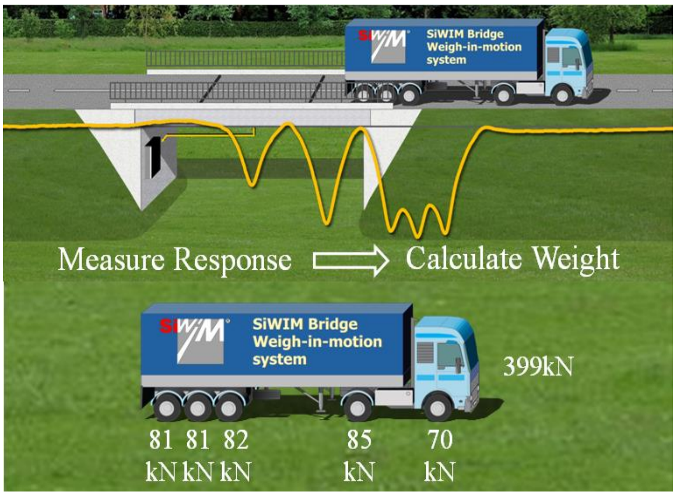

Figure 1. Bridge-WIM Concept.

B-WIM technology is quite well established for traffic load monitoring on road bridges [1, 2]. Cestel d.o.o. is a Slovenian company which markets a B-WIM system known as SiWIM. As part of BridgeMon, SiWIM is being enhanced to include novel developments in the field of B-WIM research.

While B-WIM has been applied successfully to road bridges, this is not the case for rail bridges. Accurate safety assessment of rail bridges requires a detailed knowledge of the actual train loading being experienced by the bridge, particularly on networks where the track manager does not own the railway stock. While certain technologies do exist for weighing trains, they are often very slow or cumbersome [3, 4] and are not feasible for large scale data collection on train weights. The development of a rail B-WIM system would make it possible to obtain a great deal of information on train loading which could be used in the safety assessment of rail bridges. As part of BridgeMon the B-WIM concept is being extended to rail bridges in this regard.

2.2 *Virtual Monitoring*

BridgeMon is also examining the concept of 'Virtual Monitoring' of bridges. The virtual monitoring concept uses a combination of a B-WIM system which is installed on the bridge along with a finite element model of the structure. Using the loading information obtained from the B-WIM sensors, the stresses at other locations, where sensors have not been installed, can be 'virtually' monitored. This allows stress levels at many critical locations to be measured without the requirement for a vast number of sensors. The remaining fatigue life of steel bridges can be estimated using the virtual monitoring system.

The Harmsen Bridge in the Netherlands has been instrumented for the application of the virtual monitoring concept, and work on the development of virtual monitoring software is ongoing. Figure 2 shows a photograph of the bridge along with a finite element model that has been developed for virtual monitoring.

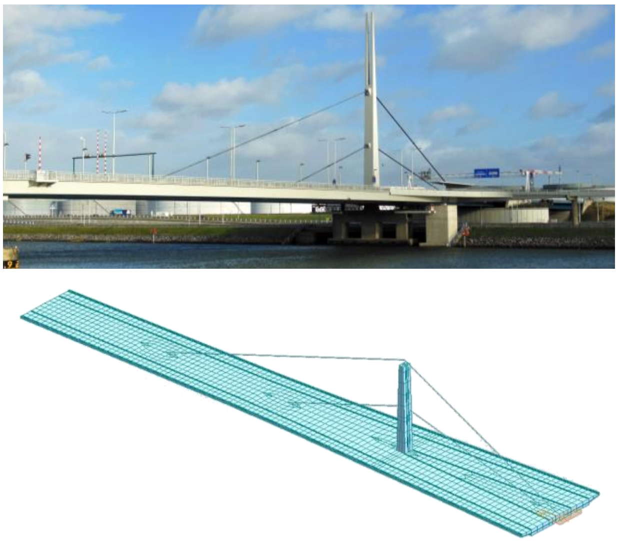

Figure 2. Photograph and FE model of the Harmsen Bridge.

2.3 *Combined Bridge-WIM & Structural Health Monitoring*

While B-WIM is primarily employed to gather information on traffic loading it can also be used in combination with a Structural Health Monitoring (SHM) system for a bridge. B-WIM relies on strain measurements from a bridge to calculate the weight of trucks or trains. Damage to a structure will very often result in a change in magnitude in the measured strains, and hence manifest itself in a change in the calculated weights. This has particular significance in railway applications where there are generally only a small number of different train locomotives whose weights remain relatively constant and changes in calculated weights would signify a change in the bridge response, possibly due to damage.
Damage to a structure can also manifest itself in changes to the dynamic characteristics, specifically the natural frequencies and mode shapes. Numerical modelling can be used to determine the optimum instrumentation setup for a particular bridge by identifying the locations most sensitive to damage.

Using the combination of B-WIM and SHM, real time monitoring of the health of a structure can be achieved. This allows the collection of loading information for a bridge, in addition to providing detailed information on its condition. Figure 3 shows a train-track-bridge interaction model which models the dynamic interaction between a train and a bridge, while accounting for the influence of the rail, sleepers and ballast. This model has been developed for use with the combined B-WIM and SHM concept. The model can be used to decide on the optimal locations for instrumentation as well as being used to simulate damage at different locations in order to aid the SHM system in detecting it.

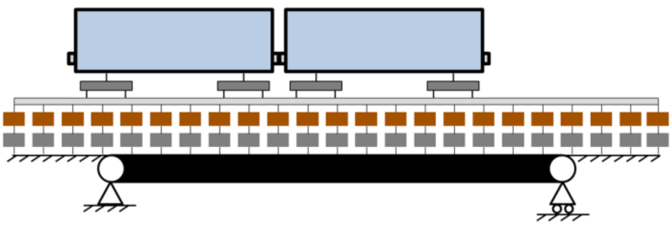

Figure 3. Train-track-bridge interaction model.

3 DEVELOPMENT OF A RAILWAY BRIDGE-WIM SYSTEM

One of the primary focuses of BridgeMon is the development of B-WIM technology as an efficient tool to gather information on traffic loading for bridges. Central to this is the development of a B-WIM system which can be used to calculate the weights of trains on railway bridges. At present, accurate weighing of trains is a slow and cumbersome procedure, which can cause disruption to railway schedules and is not convenient for large scale collection of information on train weights [3]. Procedures for weighing trains in motion do exist [5] and an attempt has been made to apply the B-WIM concept to railways [6], but with limited success.

The ability to accurately weigh trains in motion would be of great benefit to railway infrastructure managers, from the perspective of safety assessment of bridges, but also with respect to the enforcement of legal weight limits for trains.

While the B-WIM concept for road and rail bridges is very similar, there are some key differences between the two which have been identified. The accuracy of road B-WIM has been shown to be influenced by vehicle transverse position as well as the roughness of the road surface [7]. For railway applications, trains are constrained to run on tracks, which are much smoother than roads. In addition train configurations do not vary a great deal, making it less difficult to identify the axle configurations. In contrast, trains have far more axles than trucks and are heavier, which may cause inaccuracies in B-WIM predictions as a result of ill-conditioned equations in the algorithm and increased dynamics.

3.1 Bridge-WIM Theory

The vast majority of B-WIM approaches are based on the original idea proposed by Moses [8]. This conventional approach uses the assumption that the measured response (i.e. strain) from a bridge can be approximated by multiplying the axle weights of a vehicle by the corresponding influence line ordinates and summing the responses of all axles. Using this assumption, along with a known influence line for a bridge, the axle weights of the vehicle can be estimated by finding the values which provide the best fit to the measured response.

Sensors are located across the width of the bridge at a single longitudinal location (usually mid-span). The problem is generally reduced from that of two dimensions to one dimension by summing the signals measured in each of the sensors to give a single response for each train location. Figure 4 shows the assumption used within the B-WIM algorithm.

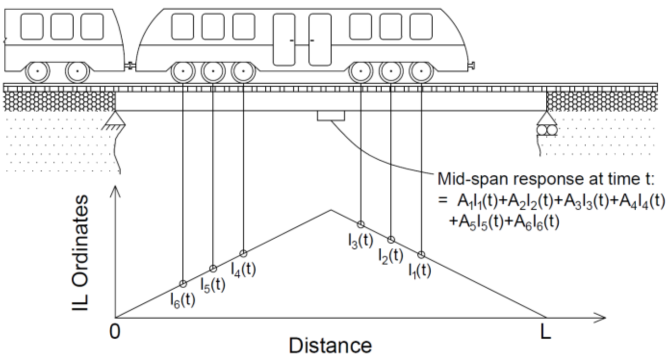

Figure 4. Basis of B-WIM calculations.

In order to solve for the axle weights, a least squares minimisation between the measured signal and the theoretical signal (based on the assumption in Figure 4) is carried out. The error function is defined as follows:

$$E = \sum_{t=1}^{T} (\varepsilon_t^{Me} - \varepsilon_t^{Th})^2 \tag{1}$$

where t is the scan number corresponding to a point in time during the crossing of the train, T is the total number of scans and ε_t^{Me} & ε_t^{Th} are the measured and theoretical strain signals at scan t respectively.

Using the assumption outlined in Figure 4 to substitute for the theoretical strain, the error function shown in Eq. 1 can be rewritten as:

$$E = \sum_{t=1}^{T} \left(\varepsilon_t^{Me} - \left[A_1 I_{1(t)} + A_2 I_{2(t)} + \cdots + A_N I_{N(t)} \right] \right)^2 \tag{2}$$

where A_n represents the n^{th} axle of the train, N is the total number of axles and $I_{n(t)}$ is the strain influence line ordinate for axle n at time t.

Differentiating Eq. 2 with respect to each of the axle weights and setting each of the partial derivatives to zero gives a set of N simultaneous equations. Solving this set of equations gives a solution for the axle weights which provides the best fit to the measured response from the bridge.

3.2 Field Testing of Bridge-WIM System in Poland

In order to assess the suitability of the B-WIM concept for measuring the weights of trains in motion, a bridge in Poland was selected for testing. The bridge (Figure 5) is located in Nieporęt, near Warsaw. The steel truss bridge was constructed in the 1970s and is one of over one thousand similar railway bridges in Poland [9].

Figure 5. Nieporęt rail bridge - for testing of B-WIM.

The bridge which spans 40m is simply supported on two bearings at either end and carries a single un-ballasted railway track. The truss consists of five bays and is 8m in height. Figure 6 shows an outline of the main structural elements (the rail and sleepers are removed for clarity).

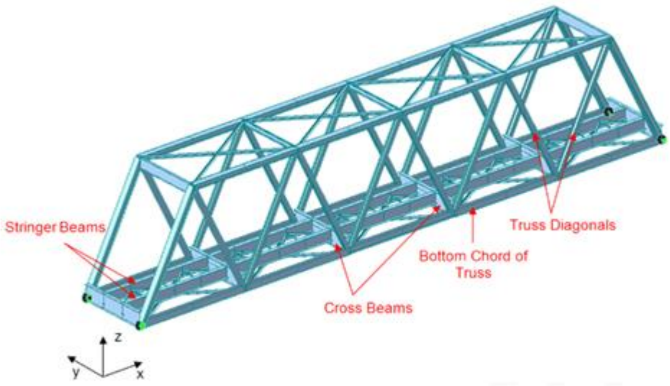

Figure 6. Structural configuration of Nieporęt bridge.

The track is supported by timber sleepers which rest on two main longitudinal stringer beams. These stringer beams span between six cross beams which are located at the node points of the bottom chord of the truss.

The bridge was instrumented with SiWIM sensors, which were attached at the locations shown in Figure 7. This figure shows a plan view of the bridge at track level. Sensors 1, 4, 5 and 8 are attached to the stringer beams, sensors 3 and 6 are attached to the bottom chord of the truss, sensor 2 is attached to the underside of the rail and sensor 7 is located on a cross beam.

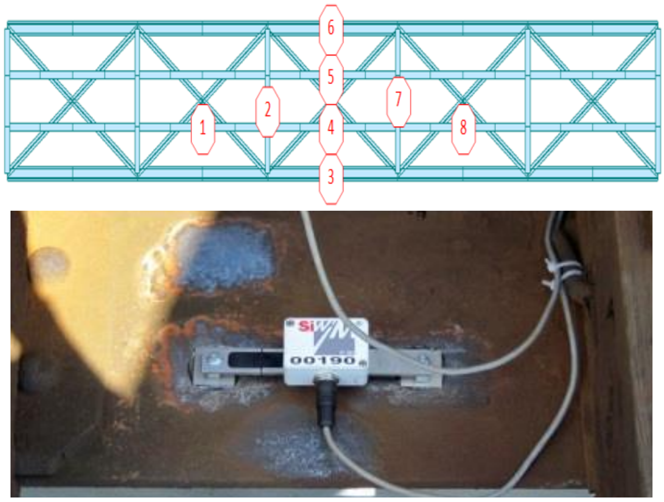

Figure 7. Sensor locations for B-WIM (above) and strain transducer (below).

When applying the B-WIM algorithm to calculate train weights, sensors 3-6 were used for applying weighing algorithm, while sensors 1 and 8 were used to calculate the speed of the train. Detection of axles was carried out using sensor 2 which recorded distinct peaks for each of the individual axles. Sensor 7 did not provide useful information for the application of B-WIM. The SiWIM software, which has been developed for use on road bridges, was re-configured to give suitable outputs for railway applications.

Over a period of three days, signals were recorded for the passage of a number of passenger and freight trains. Figure 8 shows the signals recorded in sensors 3-6 due to the passage of one of these trains.

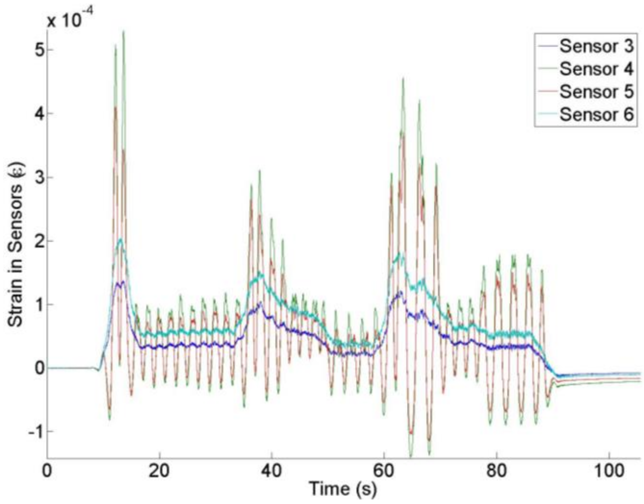

Figure 8. Measured strain during passage of freight train.

The signals shown were recorded during the passage of a freight train with a locomotive pulling 34 wagons. It is clear that the signals recorded from the stringers (sensors 4 and 5) show distinct localised peaks compared to the more global response that is obtained from the sensors measuring strain on the bottom chord of the truss.

Once the installation had been carried out it was necessary to calculate an influence line which could be used to represent the bridge response and hence be used in the calculation of weights as outlined in Section 3.1. It has been shown [10] that the theoretical influence line for a structure rarely matches the actual influence line. In order to calculate the actual influence line for the bridge, an optimisation technique, which calculates the shape of the influence line that provides the best fit to the signal, was employed. This influence line was then used within the B-WIM algorithm to calculate the weights of trains - Figure 9.

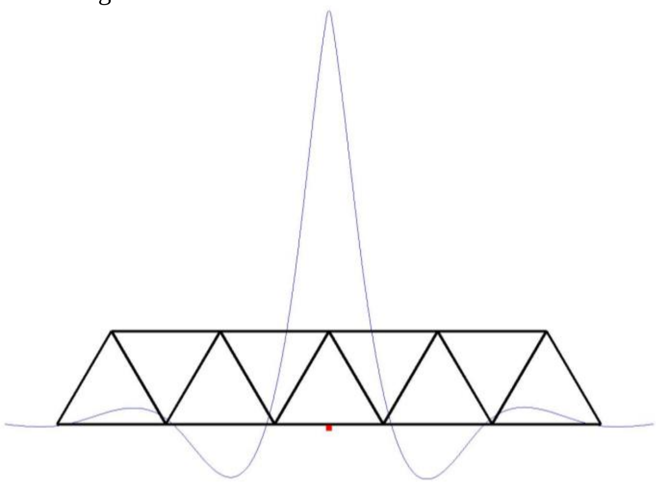

Figure 9. Influence line for mid-span bridge response.

3.3 *Low-Speed Weighing of Trains*

In order to assess the accuracy of the weights being calculated by the B-WIM system, four of the freight trains that passed over the bridge were diverted to a low-speed weighing site in a rail yard in Warsaw. These weighing scales can accurately weigh trains as they move very slowly across at speeds below 5km/h. Figure 10 shows an image of this scales.

Figure 10. Low-speed weighing scales for trains.

The low-speed weighing provided accurate weights for each of the carriages on these four trains. Using these known weights, the accuracy of the B-WIM weight predictions was assessed.

3.4 Bridge-WIM Results

The calculated weights from the B-WIM system, for each of the carriages on the four freight trains, were compared to the weights obtained from the low-speed weighing. The accuracy of the prediction for each of the carriages was then calculated. Figure 11 shows the error in the predicted carriage weights for each of the four trains.

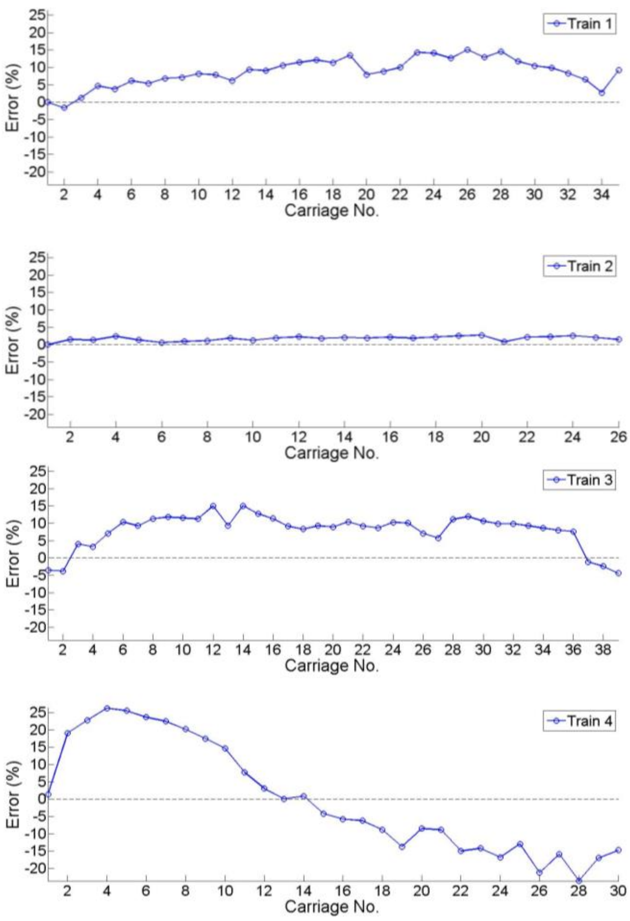

Figure 11. B-WIM prediction errors.

From Figure 11 it can be seen that the weights predicted by the B-WIM algorithm varied in accuracy. The most accurately predicted train was train 2 where all of the calculated carriage weights were within 3% of their actual weight. Train four was predicted least accurately, with an over-prediction of 26% on one of the carriages and an under-prediction of 24% on another. Trains 1 and 3 were predicted more accurately than train 4, with the worst carriage predictions for both of these trains being 15% above their actual weight.

Table 1 provides a summary of the accuracy of the weight predictions for each of the four trains, showing the worst carriage along with the average error and standard deviation of predictions.

Table 1. Summary of B-WIM Errors.

Train	Mean Error (%)	Std. Dev. Error (%)	Maximum Error (%)
1	8.72	3.95	15.06
2	1.74	0.67	2.71
3	8.81	3.27	15.10
4	13.75	7.79	26.23

3.5 Influence of Train Velocity on Accuracy

In order to carry out the B-WIM calculations, it was necessary to calculate the velocity of the train. This was done by examining the signals in sensors 1 and 8 (see Figure 7), and calculating the offset between the two signals. Using the fact that the distance between these sensors is known, the velocity of the train can be calculated.

It is important to note that a common assumption in most B-WIM algorithms is made, whereby the velocity is assumed to remain constant during the crossing. Using this assumption for road bridge applications is generally reasonable as the vehicles are short and the bridges chosen are usually quite short also. Thus their speed tends to remain relatively constant during the short time which they are on the bridge. This was found not be to be the case for the trains crossing the Nieporęt Bridge.

The trains observed during testing were between 370-630m in length with some of the trains taking nearly 3 minutes to cross the bridge. Due to a speed restriction it is unreasonable to assume that the velocity of these trains actually remained constant for the whole time that they were on the bridge. The Nieporęt Bridge has a speed limit of 20km/h, which results in trains rapidly decelerating as they approach the bridge in order to meet the speed restriction and accelerating as they leave it, while some of the rear carriages may still be on the bridge.

Comparing the calculated axle spacings for the carriages, which were obtained using the constant velocity assumption, to the actual spacings for these types of carriage allowed their individual velocities to be calculated. Examining their relative velocities for each of the four trains showed that the major inaccuracies were due to the changing velocity of the train as it crossed the bridge.

The velocity of train 4 varied over 40% during its passage, while the velocity of train 2 remained almost constant.

3.6 Suggestions for Improved Accuracy

It is expected that addressing the issue of train velocity will show an improvement in the accuracy of the railway B-WIM system. As work on BridgeMon continues, the algorithm will be adjusted to calculate the individual velocities for each of the carriages on the train rather than the average velocity of the whole train.

Some inaccuracy was also found to occur when fully loaded wagons were located adjacent to empty wagons. In these cases the individual contribution of the lighter axles could not be distinguished within the overall response in the measured signals and the predictions were less accurate. These errors result from ill-conditioning of the equations. Further work in BridgeMon will see the implementation of a numerical regularisation technique in order to reduce errors due to ill-conditioning.

4 CONCLUSION

Accurate safety assessment of bridges requires detailed information on the loading being experienced by the structure along with its health. The BridgeMon project aims to improve current bridge monitoring techniques for road and rail bridges.

This paper gives a brief overview of the work being carried out as part of the project, whereby B-WIM technologies are being advanced to develop convenient and accurate systems for monitoring traffic loading on bridges. In addition, the concept of virtual monitoring of bridges is being developed along with methods of incorporating B-WIM measurements into SHM systems in order to evaluate the health of the structure.

BridgeMon aims to apply the B-WIM concept to rail bridges for the first time, in an effort to develop the first B-WIM system for monitoring train loading. Results are presented from experimental testing of a railway B-WIM system on a truss bridge in Poland. The results for one train show that all of the carriage weights calculated by the B-WIM system are within 3% of their actual weight. Initial results for other trains show larger errors, when the effect of changing velocity is not corrected.

Work on the BridgeMon project is ongoing and the results from the experimental testing of a rail B-WIM system are promising. Further work will address the issue of inaccuracies caused by changing train velocity as well as the application of a numerical regularisation technique in an attempt to improve inaccuracies which occurred when heavily loaded carriages were located next to empty carriages.

ACKNOWLEDGMENTS

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