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Title	A filtered measured influence line approach to bridge weigh-in-motion
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Publication date	2010-07-11
Publication information	O'Brien, Eugene J., Arturo González, and Jason Dowling. "A Filtered Measured Influence Line Approach to Bridge Weigh-in-Motion." Taylor & Francis (Routledge), 2010.
Conference details	The Fifth International IABMAS Conference: Bridge Maintenance, Safety Management and Life-Cycle Optimization, Philadelphia, USA, July 11-15, 2010
Publisher	Taylor & Francis (Routledge)
Item record/more information	http://hdl.handle.net/10197/4091
Publisher's statement	This is an electronic version of an article published in Bridge Maintenance, Safety and Management - IABMAS'10: Proceedings of the Fifth International IABMAS Conference, Philadelphia, USA, 11-15 July 2010, available online at: http://www.routledge.com/books/details/9780415877862/

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A Filtered Measured Influence Line Approach to Bridge Weigh-in-Motion

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ABSTRACT: In Bridge Weigh-in-Motion (B-WIM), an instrumented bridge is used as a scales to weigh passing trucks and their axles. The most common algorithm upon which modern B-WIM systems are based remains that developed by Moses (1979). The performance of this method is well documented; it is very good at estimating Gross Vehicle Weight, but less accurate for individual axles, particularly closely spaced axles on longer bridges. Many alternatives to Moses's original algorithm have been tested and some show the potential to improve accuracy but commercially available B-WIM systems are still based substantially on the original approach. This paper proposes a method of altering the B-WIM algorithm to improve the accuracy of the predictions. The measured dynamic signal, to which the algorithm is applied, is first filtered to remove high frequency components of the dynamic increment of load. The influence line used by the algorithm is also calculated differently. As previously described by OBrien *et al.* (2006) it is determined using a pre-weighed calibration truck and an algorithm to automatically convert the corresponding measured signal into a 'measured' influence line. However, for this work, the measured signal is first filtered to remove much of the high frequency dynamic components which results in a significant improvement in the overall accuracy of the system. Moses's equations are applied as in most other B-WIM systems but, in this case, using a filtered measured influence line and a filtered signal for the unknown truck. In this way, Moses's least squares fitting method is now comparing only the low frequency components of the measured and theoretical responses and produces a much more accurate fit. The new approach is tested in numerical models and it is shown to result in a substantial improvement in accuracy.

1 INTRODUCTION

It is important that an authority charged with the keeping of a region's transport infrastructure have accurate estimates of the characteristics of the traffic fleet that make use of all the components of this infrastructure. This information has many applications, not just concerning planning, design and assessment in the area of transport, but is also of interest in relation to, for instance, the economic and social development of the area. With regard to the bridge stock of this infrastructure, the important characteristics of the traffic fleet are gross weight, axle loads, axle spacing (and wheelbase) and vehicle velocity. Weigh-in-Motion (WIM) systems are one method of obtaining this data.

1.1 *Weigh-in-Motion*

Heavy vehicles can have adverse effects on road surfaces and bridges. Legal limits for loads per axle; Gross Vehicle Weight (GVW) and overload enforcement reduces the number of excessively heavy

vehicles on a region's roads. Whether or not enforcement is effective, it is important to get unbiased, reliable data on the traffic fleet for design and assessment purposes. Pavement-based WIM systems and Bridge-based Weigh-in-Motion (B-WIM) provide methods of automatically weighing trucks at full highway speeds, and in the case of Nothing-On-Road (NOR) B-WIM, this can be achieved without even the knowledge of the vehicle drivers.

1.2 *Bridge-based Weigh-in-Motion*

The concept of using bridges as weighing scales was first proposed by Moses (1979). B-WIM systems consist of strain transducers attached to the soffit of a bridge recording strain at set intervals defined by the scanning frequency of the system (typically 256Hz or 512Hz); road surface mounted axle detectors, or extra strain transducers attached to the soffit in the case of NOR B-WIM (WAVE 2001) measure the vehicle velocity and axle spacing. An algorithm then uses these strain readings, axle spacings and velocity to infer the static axle loads. A detailed de-

scription of the process of inferring the static axle weights follows in section 2.

1.3 Dynamic Increment of Load

The use of a parameter to provide for dynamic amplification of the effect of traffic load is common among design guides and codes. There are many factors contributing to the magnitude of the dynamic load increment associated with a traffic loading event. These include vehicle characteristics (axle spacing, suspension parameters, etc.), vehicle velocity, bridge natural frequencies and road profile. The Eurocode (2003) applies Dynamic Amplification Factors (DAFs) to traffic load models and AASHTO (1996) defines a Dynamic Load Allowance (DLA) that is applied to the static traffic load. These DAFs or DLAs are necessarily conservative to allow for the large variability in dynamic amplification.

A B-WIM system is particularly well suited to the study, and quantification, of the dynamic increment of load effect, as it measures directly the total load effect (total = dynamic + static) and can infer the static load effect using the calculated axle weights. There has been much work carried out studying the relationship between the dynamic increment and load effect (Hwang & Nowak 1991, Kirkegaard, Nielsen & Enevoldsen 1997, Heywood, Roberts & Bouilly 2001, SAMARIS 2006, O'Brien et al. 2009).

Any direct measurement of dynamic increment is sensitive to the accuracy of the B-WIM estimate of static axle weights. By improving the accuracy of B-WIM systems, more accurate studies of the dynamic increment of load effect can be conducted.

2 B-WIM ALGORITHMS

The main advantage of B-WIM systems is that, unlike pavement-based WIM systems where the vehicle is in contact with the measuring equipment for a few milliseconds, the vehicle is in contact with the apparatus (i.e., the bridge) for periods of the order of one second. B-WIM systems take advantage of this fact by smoothing out the dynamic component, even if there is no active attempt to remove it.

2.1 Moses Algorithm

The algorithm developed by Moses in the late seventies remains the basis of modern B-WIM systems. The algorithm is based on the assumption that a moving load will induce strains in a structure proportional to the sum of products of axle weights and corresponding influence line ordinate values. The influence line refers to the point of measurement which is often taken as midspan, the point where strains are generally greatest.

Recording strains at regular intervals, defined by the scan number, gives a typical number of strain values of the order of hundreds. An error function is defined as the sum of the squares of the differences between theory and measurement:

$$\phi = \sum_{k=1}^S (M_k^m - M_k^{th})^2 \quad (1)$$

where S is the total number of scans; M_k^m = measured bending moment (proportional to strain) in scan k and M_k^{th} = theoretical bending moment in scan k .

2.1.1 Influence Line

The theoretical response used in Equation 1, M_k^{th} is calculated as the sum of products of the individual axle weights and the corresponding influence line ordinates for the location of each axle of the truck at the time of each scan. An example of an ideal 'triangular' influence line for a simply supported beam is shown in Figure 1.

Figure 1. (Ideal) Influence Line.

The influence line used for the calculations has a huge bearing on the resulting axle weight calculations. For the 1-D theoretical simulations described herein (simulating a simply-supported structure), the influence line depicted in Figure 1 is the true influence line used to calculate the static response. In the results section of this paper (section 4), results from this original algorithm will be presented. This will be labelled Algorithm #1. In reality, the influence line of a simply-supported bridge is not triangular and may lie closer to something between the simply-supported and fixed cases (Žnidarič & Baumgärtner, 1998). This is due to friction at the supports, load dispersion through the depth of the deck, etc..

O'Brien et al. (2006) developed a method of calculating the influence line for a bridge using measurements obtained directly from the bridge. This method is similar to the least squares method employed in B-WIM algorithms, but with the unknown in this case being the influence line ordinates as opposed to the axle weights. The result is referred to here as a 'measured' influence line.

2.2 A Filtered Measured Approach

2.2.1 Filtering

Figure 2 shows both the time and frequency domain representations of the bending moment response of a 5-axle truck crossing a 25m simply supported bridge. The response was obtained using the bridge-vehicle dynamic interaction model described in section 3.1.

Figure 2. Time and Frequency domain responses.

The dashed (black) lines in both the time and frequency domains correspond to the total bending moment, while the solid (red) lines represent the static bending moment. The noticeable peak in the total bending moment frequency domain corresponds to the first natural frequency of the bridge (4.09 Hz).

Studying the frequency domain representations of multiple vehicles, some conclusions can be made. Figure 3 shows the total bending moment frequency domain responses for ten 5-axle trucks of varying axle spacing, axle load and velocity.

Figure 3. Frequency Domain Responses of ten trucks

For very low frequencies, those less than the first natural frequency of the bridge, the amplitude of the dynamic increment (difference between total and static) is much less than that associated with the static response. Also for these frequencies lower than the first natural frequency, the static response is linear. Performing the same Fast Fourier Transform (FFT), (i.e., with similar characteristics, frequency resolution, etc.) on a number of responses from the same truck, at the same velocity but with different axle loads, the amplitudes obtained still vary linearly.

The measured response used for the B-WIM algorithm is the total response filtered (low pass filter) at a frequency lower than the first natural frequency of the bridge, in this case, say 3 Hz. Filtering the measured response in this way is not a new concept to B-WIM as it is commonly used as a method of removing much of the noise from the strain gauges. However, using filtering for this purpose would involve filtering at a higher frequency than the first natural frequency of the bridge (e.g., above about 30 Hz), leaving the signal largely intact.

2.2.2 The Filtered Measured Influence Line

To find the measured influence line, a pre-weighed calibration truck is driven across the bridge a number of different times. The adopted calibration plan consisted of 9 (simulated) runs: three loading states; (unloaded, half-loaded and fully loaded) and three velocities ($0.8v$, v , and $1.2v$ where v is the mean velocity of the traffic). The measured influence line is calculated from the strain data using the method described by O'Brien et al. (2006). The 9 measured influence lines are averaged and then filtered, in this case at 3 Hz. This algorithm will be labelled 'Algorithm #2'.

2.3 Algorithm #3

Studies show that velocity has a great influence on the dynamics associated with a loading event (Brady et al. 2006). A further step to improve the B-WIM algorithm is to counteract the influence of velocity. This third approach uses the same concept as the 'Filtered Measured' approach, but uses a different Influence Line for each truck velocity. This will be a little more difficult to implement in practice as the calibration truck will be required to cross the bridge a number of times for each velocity of interest. This is labelled 'Algorithm #3'. Table 1 summarises the three alternative B-WIM algorithms.

Table 1. Description of the algorithms.

Algorithm	Description
#1	Moses's Algorithm: Measured Total response with exact 'triangular' Influence Line.
#2	Measured Total response filtered below 1 st natural frequency of the bridge with 'Filtered Measured' Influence Line.
#3	Measured Total response filtered below 1 st natural frequency of the bridge with a different 'Filtered Measured' Influence Line for each velocity.

3 TESTING THE NEW APPROACH

3.1 Vehicle Bridge Model Description

The model used is a 1-D 5-axle articulated truck model with eight independent degrees of freedom; bouncing and pitching motion of the tractor centre of gravity; pitching motion of the semitrailer centre of gravity and vertical hop motions of each axle assembly. Harris et al. (2006) give a detailed description of this model which is illustrated in Figure 4. The model is implemented in MATLAB (2005).

Figure 4. Schematic of 5-axle articulated truck model.

Values for axle spacing, GVW, axle weights and vehicle velocity were taken, by empirical Monte Carlo sampling (OBrien et al. 2010), from a database of WIM measurements for a site located on the A196 in France (Grave, 2001).

The response of a bridge to the passage of a vehicle is strongly influenced by the condition of the road surface (DIVINE, 1997). Hence, a road surface profile is included in the model; generated in accordance with the International Standard Organisation's method of representing road surface roughness, namely, a power spectral density function. Section 4 shows the influence of road surface roughness on the results obtained.

3.2 Influence of Velocity

To show the influence of vehicle velocity on the accuracy of B-WIM systems, a single vehicle was simulated crossing a 25m span bridge. The only parameter varied in 10 simulated crossing events was

velocity. The variations in the predictions are shown in Figure 5.

The Y-axis gives the percentage error in GVW, that is, the difference between the value predicted by the algorithms and the true value, expressed as a percentage of that true value. Velocity does influence the accuracy but it should be noted that all the errors are very small and the trend is unlikely to be repeatable. It does appear that Algorithm #2 is better than Algorithm #1 and that Algorithm #3 is the best of the three. This is despite the fact that #1 is based on the true influence line – the less than perfect influence lines are giving more accurate results!

Figure 6 gives the errors in individual axle weights as a function of velocity. In this case higher speeds give better accuracy and the errors are significant – more than 15 % in some cases. For the lower speeds, in particular, there are complementary errors between the first two axles, i.e., there is a 'rocking' effect, with one axle being over-weighted and the other being under-weighted. As for GVW, Algorithm #3 is the most accurate and Algorithm #2 is more accurate than Algorithm #1. Also, the errors are less at higher velocities.

Figure 5. Influence of Velocity on GVW Predictions.

Figure 6. Influence of Velocity on Individual Axle Weight Predictions.

Figure 7 shows the Influence Lines of Algorithm #3 for the 25m span bridge, demonstrating how they vary with velocity. These have a significant effect on accuracy despite the fact that the differences between them are small. It is noteworthy that all of these influence lines are significantly different from the true triangular influence line but still give better results.

Figure 7. Algorithm #3 Filtered Measured Influence Lines.

4 RESULTS

Span lengths of 15m and 25m were used to find the influence of span length on the accuracies of the algorithms. Properties for the 25m beam are: Young's modulus = 3.5×10^{10} N/m², second moment of area = 1.39 m⁴, mass per unit length = 18 358 kg/m and first natural frequency = 4.09 Hz. The 15 m beam has the same Young's Modulus and other properties of: second moment of area = 0.5273 m⁴, mass per unit length = 28 125 kg/m and first natural frequency = 5.66 Hz. The other properties were varied using Monte Carlo simulation as described in section 3.1. The accuracies of predictions of individual axle

Figure 8. Scatter in errors of Algorithm predictions for Single Axle Weight; 25m span; Class 'A' profile.

Figure 9. Scatter of algorithm results for 25 m span with Class A profile (mean $\pm$ 1 standard deviation).

weight are shown in Figure 8 for 100 trucks on the 25m span with a Class A (very good quality) profile. Figure 9 gives a graphical representation of the variability of the results: the intervals indicate mean error $\pm$ one standard deviation. All algorithms are much more accurate for tridem weight and particularly so for GVW; errors in the latter category are generally less than 1%.

The European COST 323 group (Jacob & OBrien 1996) developed a draft WIM standard in the 1990's (COST323, 2002) which is currently being considered as a future standard of CEN, the European Standards Committee. For B-WIM, the COST 323 draft standard defines accuracy classes based on the width of the confidence intervals within which the errors fall for GVW, single axle and group of axles. All results from this simulation are presented in Table 2. It should be noted that actual accuracies may be quite different due to other non-dynamics-related sources of error – these results are only of interest for their *relative* values. The governing factor for accuracy classification is the accuracy of predictions of individual axle weight. The system allowing a different Influence Line for each velocity is, predictably perhaps, the most accurate with an accuracy classification of B(10) for the 25 m bridge on a Class A road profile.

To compare with the results of the 25m span bridge (Figures 8 and 9), Figures 10 and 11 show the results from a 15m span bridge for individual axle weight. Figure 8 shows that, for the 15m span, the individual axle weight results are much more accurate than for the 25 m bridge for all algorithms. GVW accuracies are actually less but are still very good. The better overall accuracy for the shorter span is consistent with anecdotal evidence. Details of the results are given in Table 2 where it can be seen that an accuracy class of A(5) is returned for Algorithm Nos. #2 and #3.

Figure 10. Scatter of Algorithm predictions for Single Axle weight; 15m span; Class 'A' profile.

Figure 11. Scatter of algorithm results for 15m span with Class 'A' profile (mean $\pm$ 1 standard deviation).

4.1 Influence of Road Profile

The simulations above were carried out with a Class 'A' road profile with a roughness parameter of 5.7×10^{-6} . This roughness parameter corresponds to a 'very good' road surface condition (ISO 8608 1996). To show the effect of the road surface profile, simulations were also run using a Class 'B' road surface profile with a roughness parameter of 20.6×10^{-6} corresponding to a 'good' condition.

The governing category for accuracy classification is again the individual axle weight category.

Figures 12 and 13 illustrate the scatter and range of errors for all three algorithms. For the rougher, Class 'B' profile, the predictions are considerably worse than before. These errors are significant, highlighting the importance of the road surface condition for the accuracy of a B-WIM system. It can be concluded that the combination of a longer span (25 m) bridge, high dynamics and a rougher road profile, results in relatively poor B-WIM accuracy. Table 2 lists the means and standard deviations of the errors from the three algorithms used to classify the systems.

Table 2. Algorithm Errors & Classification.

	25m span, road profile class 'A'			Class
	Single Axle	Group of Axles	GVW	
μ -Alg.#1	12.0	0.3	0.4	D+(20)
σ -Alg.#1	5.6	1.4	0.2	
Ind. Class	D+(20)	A(5)	A(5)	
μ -Alg.#2	8.2	0.3	0.1	C(15)
σ -Alg.#2	4.8	1.5	0.2	
Ind. Class	C(15)	A(5)	A(5)	
μ -Alg.#3	5.0	0.2	0.03	B(10)
σ -Alg.#3	5.0	1.5	0.2	
Ind. Class	B(10)	A(5)	A(5)	

	15m span, road profile Class 'A'			Class
	Single Axle	Group of Axles	GVW	
μ -Alg.#1	2.0	1.0	0.5	B+(7)
σ -Alg.#1	3.2	0.8	0.3	
Ind. Class	B+(7)	A(5)	A(5)	
μ -Alg.#2	0.5	0.1	0.2	A(5)
σ -Alg.#2	2.3	0.8	0.2	
Ind. Class	A(5)	A(5)	A(5)	
μ -Alg.#3	0.6	0.7	0.6	A(5)
σ -Alg.#3	2.2	1.1	0.4	
Ind. Class	A(5)	A(5)	A(5)	

	25m span, road profile class 'B'			Class
	Single Axle	Group of Axles	GVW	
μ -Alg.#1	15.5	4.7	0.3	E(55)
σ -Alg.#1	20.6	3.7	0.3	
Ind. Class	E(55)	B(10)	A(5)	
μ -Alg.#2	10.0	4.6	0.4	E(40)
σ -Alg.#2	17.6	3.3	0.2	
Ind. Class	E(40)	B(10)	A(5)	
μ -Alg.#3	5.0	4.1	0.8	E(30)
σ -Alg.#3	13.7	2.7	0.3	
Ind. Class	E(30)	B+(7)	A(5)

Figure 12. Scatter of Algorithm predictions for 'Single Axle' (25m span, Class 'B' profile).

Figure 13. Scatter of algorithm results for 25m span with Class 'B' profile (mean $\pm$ 1 standard deviation).

5 CONCLUSIONS

Two B-WIM algorithms were developed and theoretically tested with a numerical truck model. Applying a low-pass filter to the measured response removes much of the dynamic component. In addition, and central to this approach, is the inclusion of the same filtering process to the measured influence line. Filtering below the first natural frequency of the bridge, allows much of the dynamic component to be removed while maintaining the majority of the static components intact. Fitting a theoretical static response computed using the 'Filtered Measured' Influence Line to the filtered measured response, results in a more accurate prediction of the axle weights. This may be due to the linear relationship between amplitude and axle weight in the frequency domain. The third algorithm proposed, using a different influence line for each velocity, while being more difficult to implement, further improves the axle weight predictions.

6 ACKNOWLEDGEMENTS

The authors acknowledge the financial support received from the European 7th Framework ASSET project (Advanced Safety and driver Support for Essential road Transport).

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