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Contactless Bridge Weigh-in-Motion

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Abstract

Bridge Weigh-in-Motion uses existing bridges to find the weights of vehicles that pass overhead. Contactless Bridge Weigh-in-Motion (cBWIM) uses bridges to weigh vehicles without the need for any sensors to be attached to the bridge. A camera is mounted on the back of a telescope which magnifies the image to the extent that sub-millimeter bridge deflections can be measured accurately. A second camera is used to monitor traffic and to determine axle spacings. The two cameras are synchronized using LEDs activated by an interval timer. The exact position of the test vehicle relative to the bridge influence line is determined by optimization at a post-processing stage.

The new WIM concept is tested on a bridge in the United Kingdom. In a modest test sample of eight statically weighed vehicles it is shown to be a feasible alternative to other forms of WIM. Accuracy of gross weight is already reasonably good; accuracy of groups and individual axles will require greater magnification or additional cameras.

Introduction

Statistics on truck weights are in demand for several reasons – overweight trucks adversely affect safety, pavement condition and the risk of bridge overload. In the past, trucks were weighed using static scales. This process requires the subjective selection of trucks for weighing and can be further biased by drivers of illegally overloaded trucks avoiding known weigh station locations (Sivakumar et al. 2011). For a truck operating every day in Europe, the mean time between checks is nearly 30 years (Jacob & Feypell-de La Beaumelle 2010) and those trucks that are selected for weighing may have to wait over 30 minutes. The concept of weighing trucks in motion (WIM) dates from the 1950's (Lee & Garner 1996). Modern WIM systems have better accuracy and durability properties than the early systems and provide unbiased data on gross vehicle and axle weights and spacings. They also provide headway information, crucial for bridges where extreme loading events are governed by events with multiple vehicles (Sivakumar et al. 2011).

An advantage of WIM systems is that they give a continuum of data rather than the discrete data points provided by weigh stations. Developing statistical data to describe loads is one of the essential components in a probability based approach to design and assessment (Ellingwood & Galambos 1982). Ghosn & Moses (1986) investigated how data on truck loading and bridge response provided by WIM sites can be used to change the modelling of bridge loads in specifications. In developing a live load model for bridge codes Nowak (1993) notes that the number of vehicles and truck proportion is site-specific. By assessing site-specific bridge traffic loading, bridges which may have been replaced or rehabilitated may often be deemed safe (Žnidarič 2006).

Bridge Weigh-in-Motion (BWIM) is the concept of using instrumentation on an existing bridge to weigh the vehicles that pass overhead. A good overview of the development and implementation of BWIM is given by Richardson et al. (2014). Early BWIM systems incorporated axle detectors on the road surface (Moses 1979) and had a similar traffic disruption problem to other technologies. More recently, it was shown (Žnidarič et al. 1999) that sensors underneath the bridge can be used to accurately identify the time at which an axle passes. Systems based on that principle are known as free-of-axle-detector (FAD) (WAVE 2001) or nothing-on-the-road (NOR) BWIM (Kalin et al. 2006; OBrien et al. 2008).

In a BWIM system, the bridge is acting as a weighing scales. In a conventional installation, the axle weights are found by comparing theoretical static and measured responses to the passing of the vehicle. The sum of the squares of differences between the measurements and the expected response is minimized. This concept, developed by Moses (1979), is at the heart of most modern BWIM systems.

BWIM systems, by their nature, give information on the bridge response and more accurate information on the dynamics of the bridge improve the results of bridge assessment. Žnidarič et al. (2008) use BWIM technology to calculate the dynamic amplification factor, i.e. the ratio of total to static bridge response, for each vehicle crossing event. OBrien et al. (2010) recommend the use of the ratio of characteristic total response to characteristic static response, termed the assessment dynamic ratio. WIM data is used to find the characteristic static response.

While NOR BWIM has the advantage of not requiring a road or lane closure, it does require the bridge to be instrumented and access to the underside of a bridge is sometimes problematic. The goal of this research is to test the concept of using video cameras and image analysis for BWIM, eliminating the need for any physical contact with the bridge. This process of 'contactless Bridge Weigh-in-Motion' (cBWIM) would give infrastructure managers a tool with minimal worker safety implications. This would also extend the range of bridge sites suitable for BWIM (Mahmoudabadi & Seyedhosseini 2013; Enright et al. 2012). A further advantage of cBWIM is the speed of on-site implementation – typically less than an hour – meaning same day data collection when the equipment is on site.

Conventional BWIM uses strain sensors to infer vehicle and axle weights using the static equations of equilibrium and compatibility. Bridge deflection and the dynamic relationships between force and displacement are used in moving force identification (MFI), which finds the force history of the axles and not just the static weight (Chan et al. 2001; González et al. 2008; Cai 2010; Deng & Cai 2010). However, in the past, measuring deflection accurately at high speed was difficult and has only become practical in recent years. Nassif et al. (2005) assess the use of permanent contact sensors in comparison to the use of a laser Doppler vibrometer in measuring deflection and find that the two systems compare well.

Measuring bridge deflection using images is considerably less expensive than laser vibrometry. It is carried out by either monitoring a number of points along the length of the bridge (Jauregui 2003, Jiang 2008) or one specific target point (Stephen et al. 1993; Lee et al. 2007). The application of this technology to BWIM at this point in time is, to the authors' knowledge, unique to this paper.

Equipment

The displacement measurement system in this paper consists of high-speed deflection capturing by a digital camera attached to a telescope, and motion tracking using a digital correlation method.

Apparatus

The authors surveyed the performance of several cameras with high-speed movie mode available in the consumer market. The selected Single Lens Reflex (SLR) camera, Panasonic Lumix DMC-FZ200 has F2.8 Full Range Brightness Aperture and LEICA DC VARIO-ELMARIT Nano Coating Lens with 24× optical zoom (25 to 600 mm), and also has high-speed movie modes of 120 frames per second (fps) (1280x720 pixels), and 240fps (640×480 pixels). Scanning speed of 120fps is selected by reason of the required brightness, time duration for one file, and spatial resolution. Image files are recorded on an SD memory card as MP4 files, and the maximum time duration for one file is 7 min 29 sec (54,000 frames) at 120 fps. This time duration is from a limitation of the file size in the SD memory card (4GB) and can be expected to increase as memory card capacities increase. File format is converted as AVI format in post processing by Pazera Free MP4 to AVI Converter. Capturing bridge deflection requires quite a high magnification. An alternative approach to a super telephoto lens for SLR cameras is to use an optical telescope with a teleconverter. This technique, called "Digiscoping", achieves a low cost and light-weight long range lens system. In this project, a Vixen GEOMA EDII-52S telescope with a 14x eyepiece (Vixen GL-20), is attached to the camera through a teleconverter (Vixen DG-FS DX). The total focal length is approximately 8,400 mm in 35 mm-equivalent value.

The mount system (Figure 1) is one of the key issues in capturing dynamic bridge deflection. High stiffness is required for stable pictures and smooth and fine operability when aiming at the bridge. The authors modified a theodolite (second hand, TOPCON AG-20P) on which was mounted the camera and telescope. The theodolite provided a camera platform with fine adjustment capability. A custom designed mounting attachment was manufactured to connect the camera/telescope system to the theodolite. A wooden surveying tripod (Myzox PMW-OT) provided a sturdy support system and damped out some vibration.

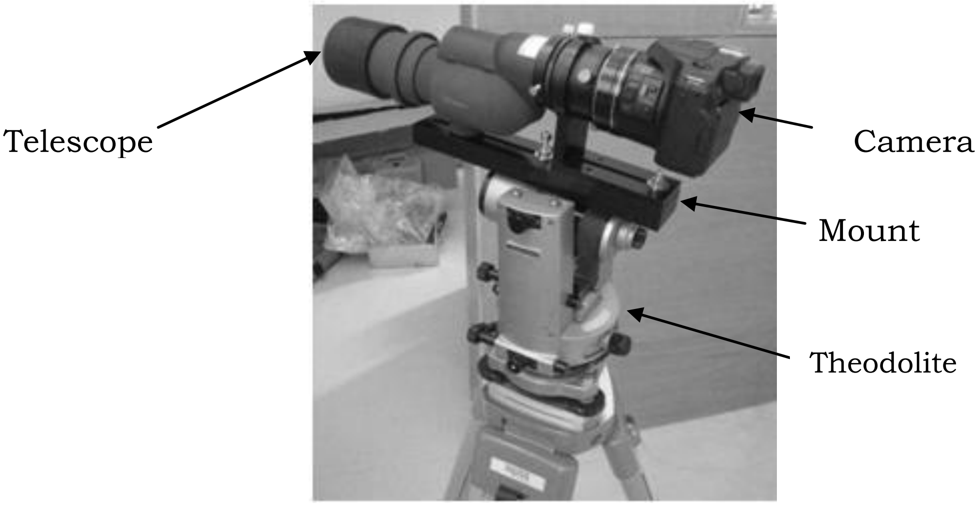

Figure 1Lens and mount system

Calibration

In conventional methods of deflection measurement by image analysis, a target which has a specific size and high-contrast appearance is attached to an object to get information on length per pixel. However, to be true to the "contactless" concept, an alternative approach was used in this study. Figure 2 shows the relationship between distances to the object and the captured image size for the 24x zoom factor obtained in preliminary measurements. If distance from the camera to the object is known, displacement can be found from the image size and pixel displacement. Distance to the object is measured by a laser distance meter. By this method, two-dimensional movement is projected on a plane perpendicular to collimation direction. It should be noted that the cBWIM system will be calibrated using a truck of known weight. Results are therefore unaffected by any inaccuracy in the absolute deflections – only the repeatability from one deflection measurement to the next is important.

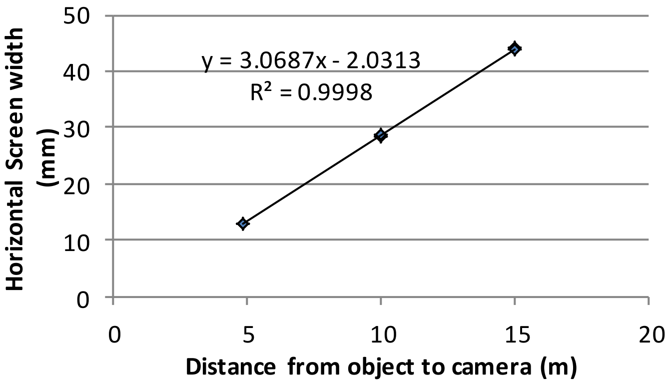

Figure 2 Distance and captured size

Installation

A camera for deflection measurement (Camera 1) was positioned in the underpass of Loughbrickland Bridge in Northern Ireland, as shown in Figure 3. The camera was focused on a sensor mounting bolt in the mid-span of girder No. 9. The location had insufficient natural light in the wintertime when measurements were taken so two 750W pin-spot lights with 19 degree beam angle were installed as additional light sources. A similar camera was set up on the bridge surface as an axle detector (Camera 2) and the two cameras were synchronized as described in the following sub-section. Sample images in the two cameras are shown in Figure 4.

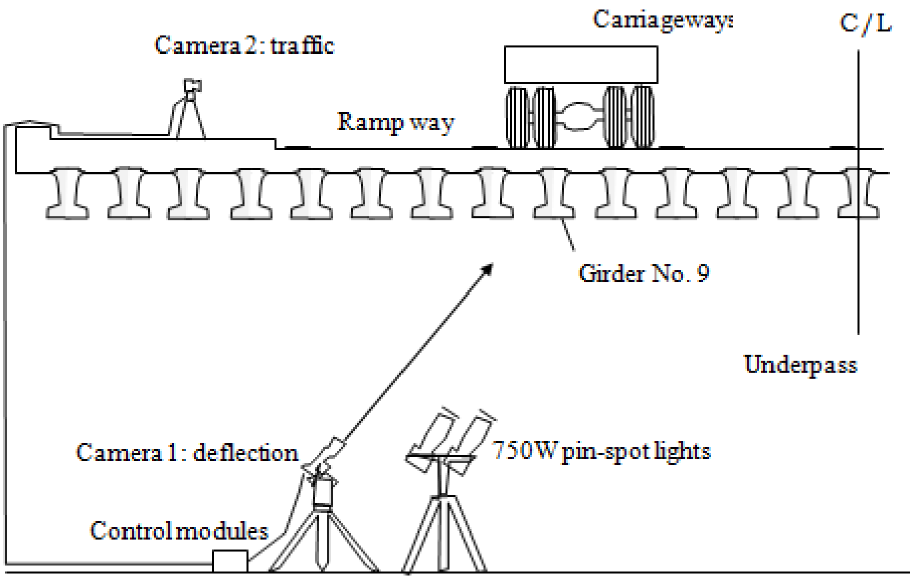

Figure 3 Layout

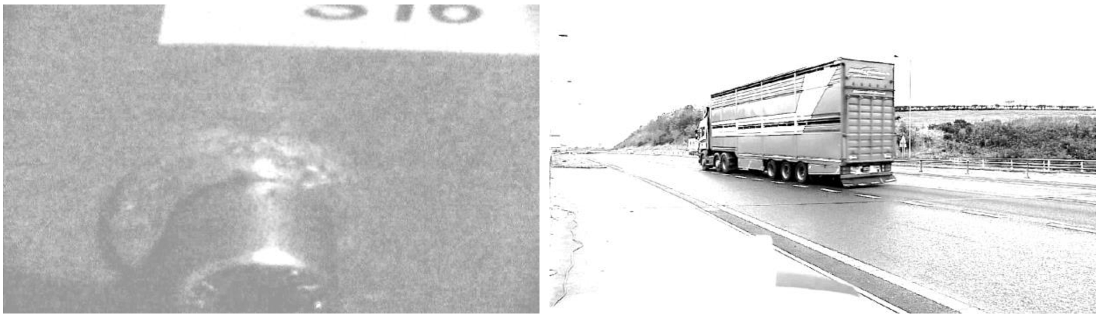

Figure 4 Example Images (a) Camera 1: Bolt on girder used as a focus point to monitor deflection; (b) Camera 2: Passing truck

If truck type or vehicle speed is calculated by image analysis from the movie image of Camera 2, the location of the camera should be selected carefully. There are two important points; one, that the camera should have enough spatial resolution which enables detection of individual axles; and the other is that there is a long enough time duration of vehicles in the movie. This is because vehicle speed is calculated by time to travel a certain distance, and the time duration is obtained only by counting frames. In an ideal situation, the camera for bridge deflection would be set perpendicular to the direction of deflection. However, if enough spatial resolution is obtained, the camera for deflection can be set at an angled position to bridge deflection.

Synchronization

The two cameras were triggered by an interval timer through a relay module driven by solid state relays (Figure 5). In order to test the synchronization potential and time accuracy, a preliminary test was carried out. While the cameras were triggered simultaneously, time delays from the trigger to the start of image capturing were not identical in each. A time difference of up to 0.1 second was observed. The timing clock itself was found not to be the source of the error – accuracy was confirmed to be within 20 parts per million. That means that if the same image were sent to the two cameras from the timer and they captured images for the maximum time duration of 54,000 frames, only 1 frame difference would occur in that duration at most. Therefore, a pair of high luminance Light Emitting Diodes (LED's), which have a very fast response time, were activated by the timer within 'sight' of each camera and used as a synchronizing timing marker (Figure 6). The lights were flashed once within one period of capture (duration 7 min, 29 sec) and appeared simultaneously in the two video streams. The picture frames containing the light were found at the post processing stage.

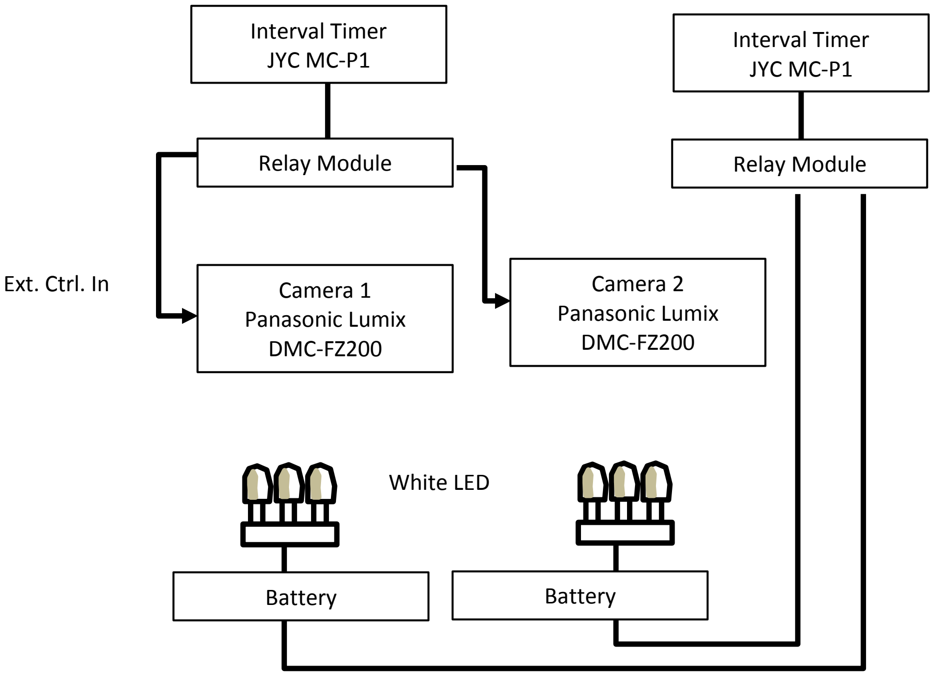

Figure 5 System diagram of control

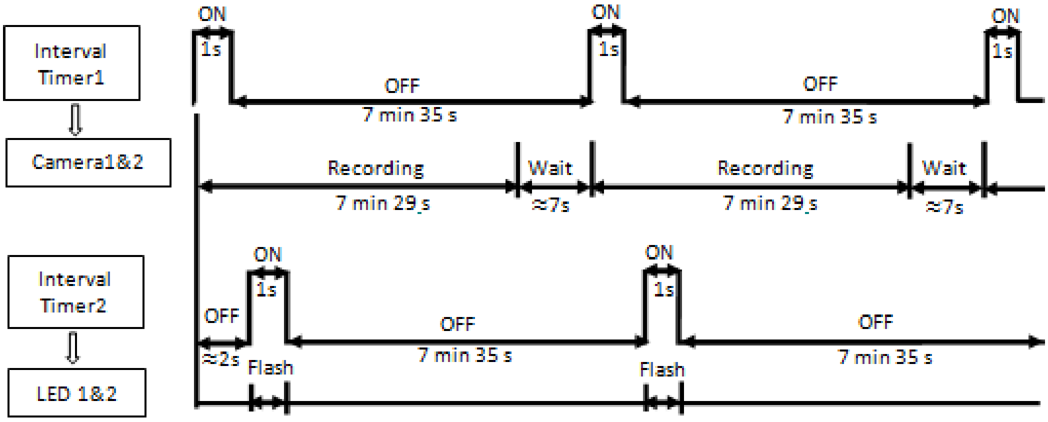

Figure 6 Control sequence of camera system

Image Analysis

Motion tracking which calculate 2-D or 3-D displacement from a digital movie image, is widely used for several research fields recently. Software packages are supplied for general use. For the post-processing stage, a software package (PV-Studio 2D, L.A.B Co., Japan) for motion tracking was used. This software uses the Lukas-Kanade method for the motion tracking algorithm. Movement of the target point is calculated at a sub-pixel dimension. A selected point of a picture frame is tracked in each frame and the time history of two-dimensional movement is generated. Figure 7 shows a result of a deflection wave and a picture of the corresponding truck. It can be seen that bridge deflection histories with maximum deflections as little as 0.2 mm can be effectively captured.

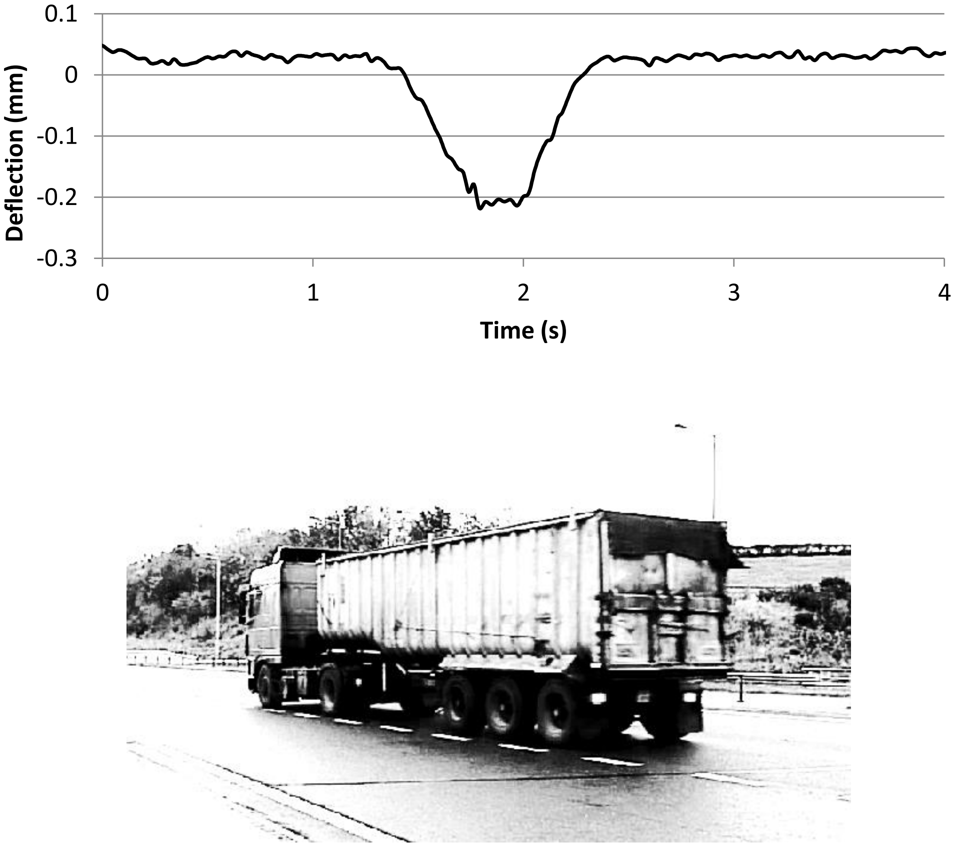

Figure 7 (a) Example of deflection/time history (b) Example picture of truck (Camera 2)

Theory and Numerical Modelling

As mentioned earlier, Moses' algorithm (1979) minimizes the squared differences between the measured and theoretical responses to find the static axle weights:

$$E = \sum_{k=1}^{K} [M_k^m - M_k^t]^2 \qquad 1$$

where E is the error, k is the scan number, K is the total number of scans and M_k^m and M_k^t are the measured and theoretical responses respectively at scan k. The theoretical response is calculated using the influence line of the bridge and is a function of the unknown axle weights. Setting the partial derivatives of the error function (1) to zero, gives the axle weights that minimize E. Figure 8 shows calculated deflection from near mid-span of a 24 m finite element (FE) beam model with road profile class "A" as it is traversed by a 2-axle vehicle. The vehicle, as seen in Figure 9, is modeled as a spring and dashpot half car model.

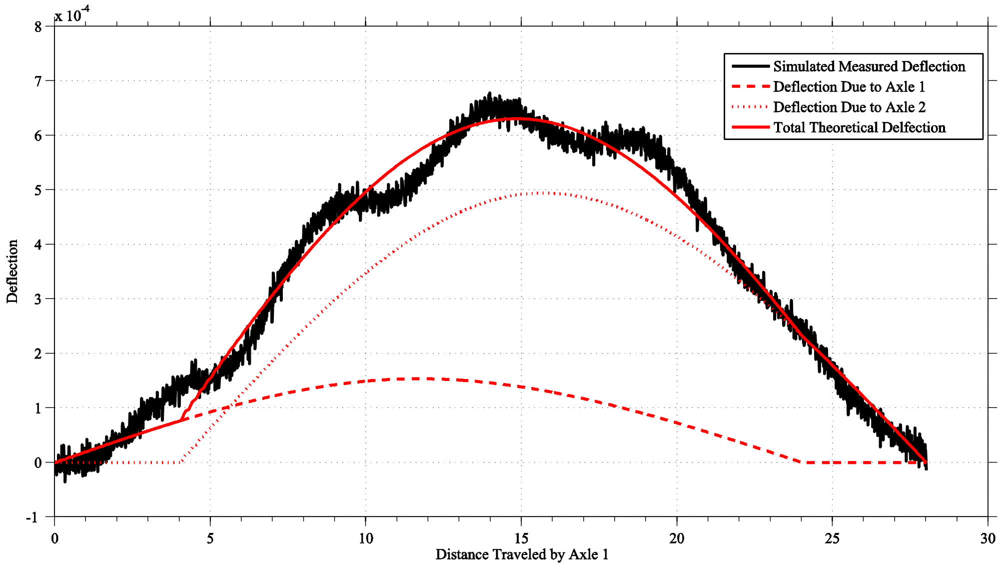

Figure 8 Measured vs. Theoretical Deflection and breakdown of Axle 1 and Axle 2 contributions

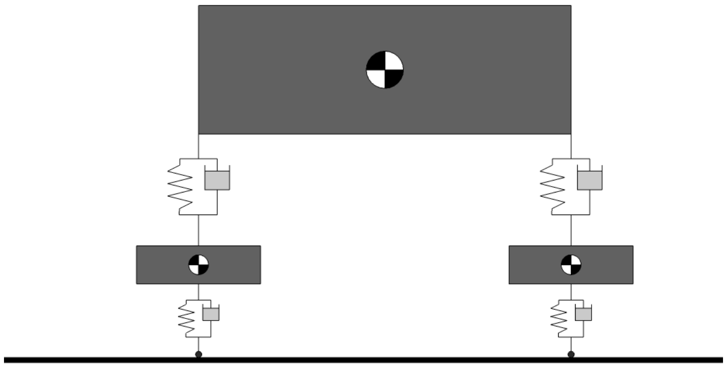

Figure 9 Half Car Model

Random noise is added to this simulated deflection signal and it is used as the 'measured' signal from which the axle weights will be calculated using the BWIM algorithm. The bridge's theoretical influence line (deflection per unit axle load) is used to calculate the axle weights from the deflection measurements. Figure 8 also shows the total "theoretical" deflection which is the summation of the products of the true axle weights and corresponding influence line ordinates for each individual axle.

The bridge response most usually used in BWIM is strain. Simulations are carried out here to compare the use of strain and deflection. Measured bridge response varies considerably from simple beam theory due to the multifaceted response of beams and plate that make up a bridge system as well as the dynamics of the vehicle and the interaction of the two systems. Therefore, to find the influence line in conventional BWIM installations, it is 'back-calculated' from the measurements corresponding to a truck of known weight. This is done by finding the best fit of measured to theoretical, that is, finding the influence line that minimizes E in Equation (1). The best fit can be found by engineering judgment (Žnidarič & Baumgärtner 1998; McNulty & OBrien 2003) or by differentiating with respect to each influence ordinate and setting the derivatives to zero (OBrien et al. 2006). In a typical installation, a modest number of runs, using one or two trucks of known weight, are used to find the influence line. Here, to avoid random bias, one thousand 2-axle trucks are used in the simulated calibration process. These are simulated crossing a 24 m finite element beam model made up of 24 number 1 m finite elements with modulus of elasticity 3.5×10^9, second moment of area of 1.15 m^4 and density of 2400 kg/m^3. The axle weights, speed and spacings are taken as a random sample from piezo-quartz WIM data of over one hundred thousand 2-axle vehicles in the Netherlands. The other vehicle properties such as suspension stiffness and damping, and tire stiffness are generated assuming normal distributions with means of 1×10^6 N/m, 5×10^3 Ns/m and 1×10^6 N/m respectively. The mean simulated 'measured' influence line is found and is used in the BWIM algorithm. The influence lines representing measurement at mid-span are illustrated in Figure 10 and show an element of dynamics as a result of the mean truck behavior in the calibration fleet.

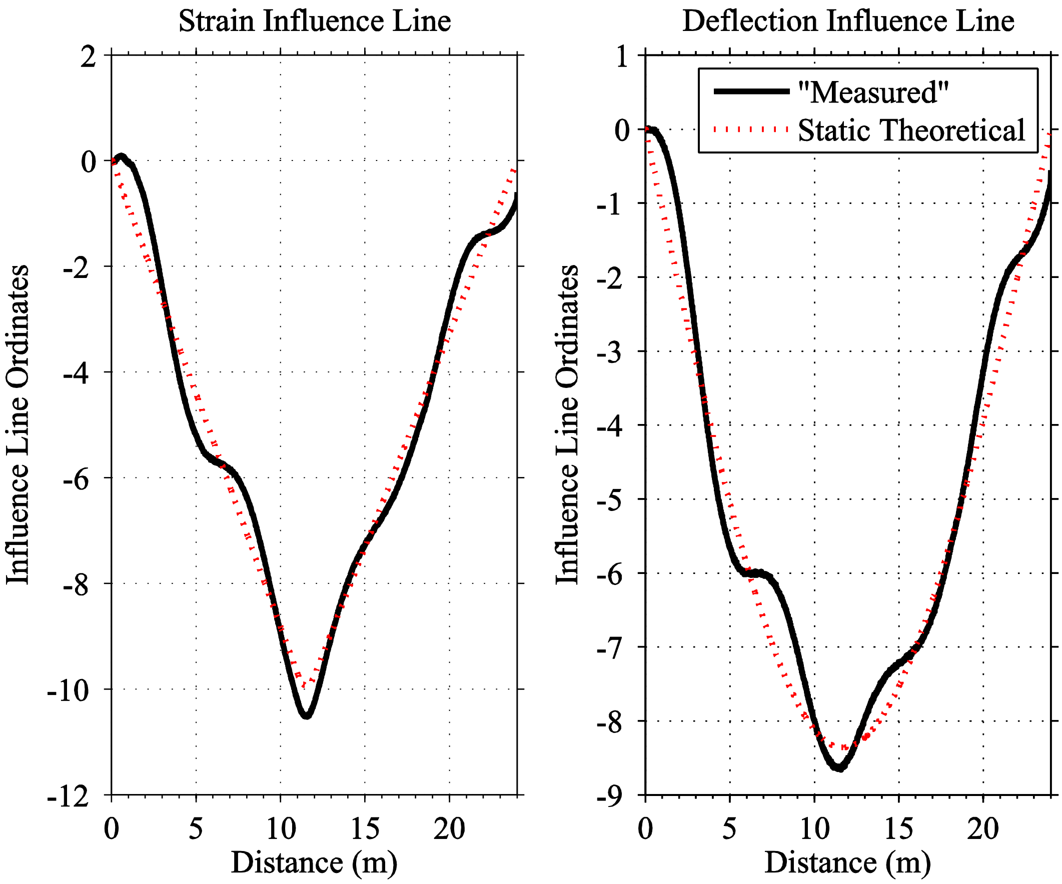

Figure 10 Measured and Theoretical Influence lines

A further batch of one thousand vehicles is simulated (dynamically) crossing the model and the BWIM approach of minimizing E in Equation (1) used to find the axle weights. This process is carried out for strain and deflection responses. The results of the simulations are shown in Table 1. The first column is the mean of the absolute values of the differences between the WIM weights, X_w, and the actual weights, X_a, divided by the actual weights. The second column is similar to the first except that it is not absolute values. This column illustrates why the gross vehicle weight estimation can be more accurate than either axle weight. If the axle 1 and axle 2 estimation errors are of opposite sign, i.e. overweighing one and under-weighing the other, then the gross weight estimation may be more accurate than both. The final column shows the maximum absolute error in order to give an indication of the worst results.

The results presented in this section illustrate the potential use of deflections in measuring the weights of vehicles. It can be seen that BWIM using deflections perform just as well if not better than BWIM using strains. These simulations are of course highly idealized - there is no road surface roughness, no noise added to the strain or deflection signal and the axle spacings and weights used in both the influence line generation and BWIM process are exact. The entire exercise was repeated using a theoretical influence line. In a third batch of 1000 simulated vehicles, BWIM using both deflection and strain gave considerably reduced accuracy.

Table 1 Results for Measured Influence Line

Measurement used and weight parameter estimated	Mean absolute error	Mean error	Standard deviation of error	Maximum error
Deflection				
Axle 1	0.84 %	-0.22 %	1.03 %	3.13 %
Axle 2	0.70 %	0.16 %	0.98 %	4.09 %
Gross Vehicle	0.26 %	-0.02 %	0.43 %	2.91 %
Strain				
Axle 1	1.04 %	-0.20 %	1.47 %	19.79 %
Axle 2	0.82 %	0.10 %	1.40 %	21.35 %
Gross Vehicle	0.33 %	-0.01 %	0.54 %	3.99 %

Field Measurements

The site and bridge selected for this testing is one that is being used by the Queen's University Belfast as part of a US/Ireland research project. The bridge is situated in Loughbrickland, Northern Ireland, along the A1 dual carriageway. This is the main corridor connecting the cities of Belfast and Dublin. The structure is on a central route through the island and has a high traffic volume which makes this an optimum location to carry out the study on cBWIM. There are 10,000 to 12,000 vehicles travelling on the carriageway in each direction daily. The bridge is in close proximity of a weigh station for trucks and local enforcement.

The bridge, which was constructed in 2010, takes the form of an integral structure with a 19 m span (Figure 11). The superstructure consists of 27 no. prestressed concrete Y4 girders, each 1 m in depth, spaced at 1.22 m centers. There is a 200 mm overlaid cast in-situ concrete deck which is supported by permanent GRC formwork spanning transversely between the main girders (Figure 12). The bridge has an angle of skew of 22.7°.

Figure 11 Loughbrickland Test Bridge

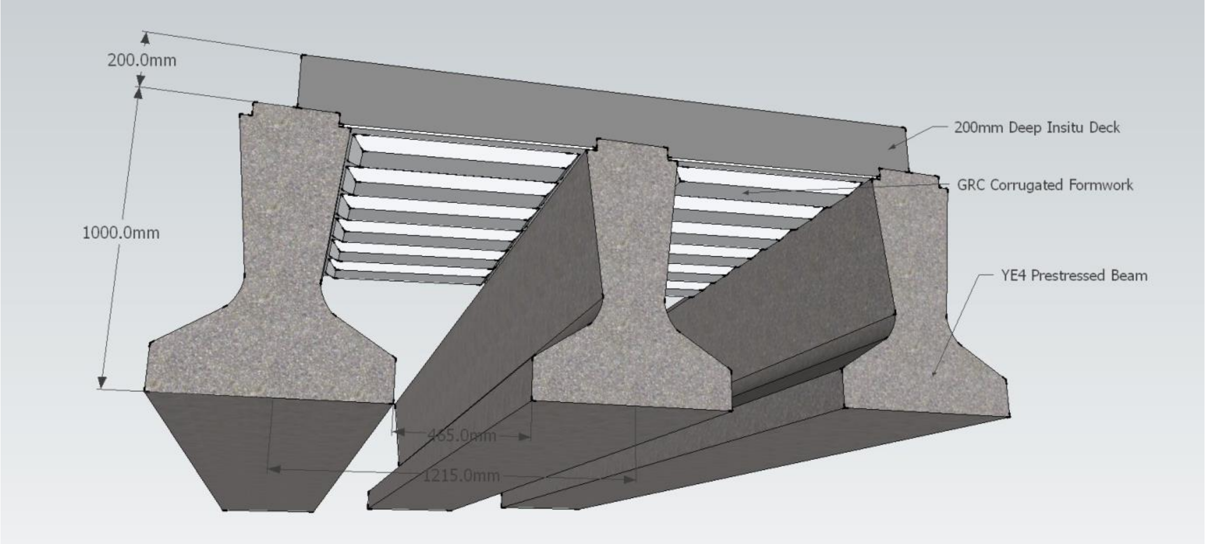

Figure 12 Loughbrickland Bridge Girders

Lane 1 of the northbound carriageway has been instrumented for BWIM application research as part of the on-going US/Ireland project. Fiber Optic sensors were installed on the girders at various locations to provide data for a conventional BWIM installation. Sensors were also installed at the supports for axle detection. Additional sensors are located on the deck slab to improve the accuracy of axle detection and investigate sensitivity to variations in vehicle transverse lane location. These additional sensors ensure that local wheel strains are not missed. All fiber optic sensors were connected back to the light source and interrogator mounted with the processing computer.

The research has benefited from collaboration with the Driver and Vehicle Agency (DVA) of Northern Ireland. They are a public team who select vehicles from passing traffic to be weighed at the nearby Weigh Station. They can enforce prosecutions on drivers whose vehicles do not conform with weight or road worthiness legislation. The DVA shared weight result information of statically weighed vehicles against which the BWIM and cBWIM installations could be checked.

Results

The measurements were taken on site over the course of one day with the cBWIM weights compared to the known weights from the static weighing by the DVA. On the day of testing, eight vehicles were statically weighed: three 5-axle vehicles, two 2-axle vehicles and one vehicle each with three, four and six axles. Due to the very limited sample size, the influence line calibration was carried out using just the three five axle vehicles. These were chosen as they are the most frequent truck type in the sample. The influence line was calculated using the matrix method (OBrien et al. 2006). The axle spacings were acquired using the video images of the vehicles traversing the bridge. The synchronization of the two cameras meant that the axle spacings could be calculated from the number of frames between the axles passing a notional vertical line in the frames.

A complication in both the calibration process and WIM calculation arises due to the unknown point at which the vehicle and bridge interact. This is partly because of the integral nature of construction which causes the axles to apply force through the soil to the bridge before arriving on the deck. In addition, because of the skew, the wheel on the right hand side of the vehicle enters the bridge first and this is the opposite side from the camera. This problem is addressed through an optimization process, where the start point of the deflection record is selected which minimizes E in Equation (1). The process will also correct any inaccuracy in the camera synchronization (Section 2).

Figure 13 illustrates the fit of the measured deflection curve to that of the curve calculated from the influence line. The calibration process ensures that the mean amplitudes match. What is more reassuring is that the general shapes are similar.

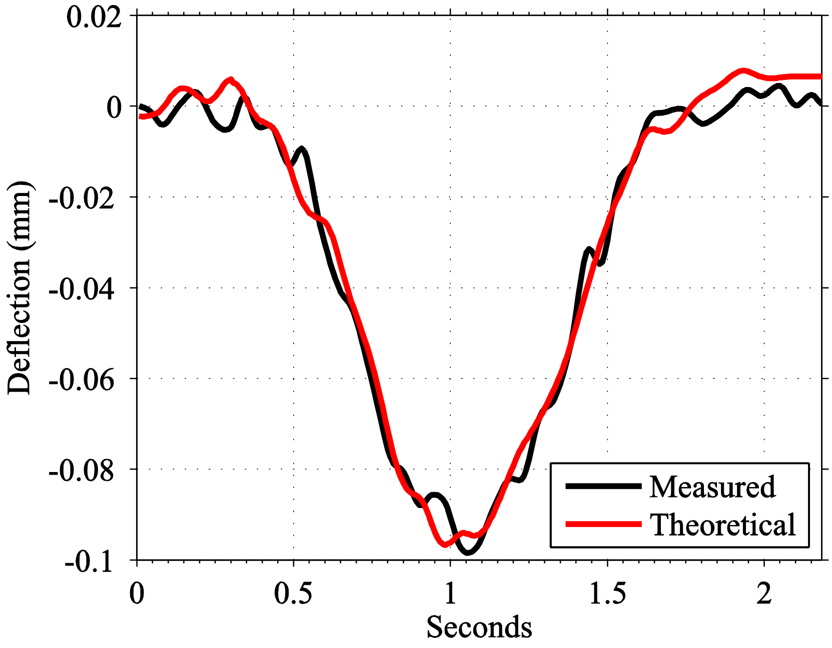

Figure 13 Measured vs Theoretical Deflection

The cBWIM accuracies for the eight vehicles weighed statically by the DVA are shown in Figure 14 and Table 2. The three 5-axle vehicles, Nos. 1-3, are used for calibration so they might be expected to have better accuracy than the five test vehicles, Nos. 4-8. However, the gross weight accuracy of the two data sets is similar. While it is less than the accuracy of a conventional BWIM system, it is reasonable and shows that the concept of cBWIM is feasible. The individual axle weights and axle group weights are of poor accuracy. The weights of the axles within the groups are particularly poor. This is unsurprising – BWIM is known to have superior accuracy for gross weights and to be less effective at finding the weights of closely spaced axles.

In order to investigate how the accuracy would be affected by a higher scan rate as well as on bridges of differing length, further theoretical simulations are undertaken. Drawing from the same population of two-axle vehicles as earlier, four scenarios are simulated, each with five hundred vehicles. Four bridges of length 10, 15, 20 and 25 m are considered with the bridge response of deflection used to infer axle and gross weights. In order to model sensitivity to measurement accuracy, random noise added to the deflections at a consistent level across all bridges and measurement points. Gaussian white noise is used with a signal to noise ratio of 20 where the signal is the mean mid-span deflection of three thousand vehicles crossing a 20 m bridge.

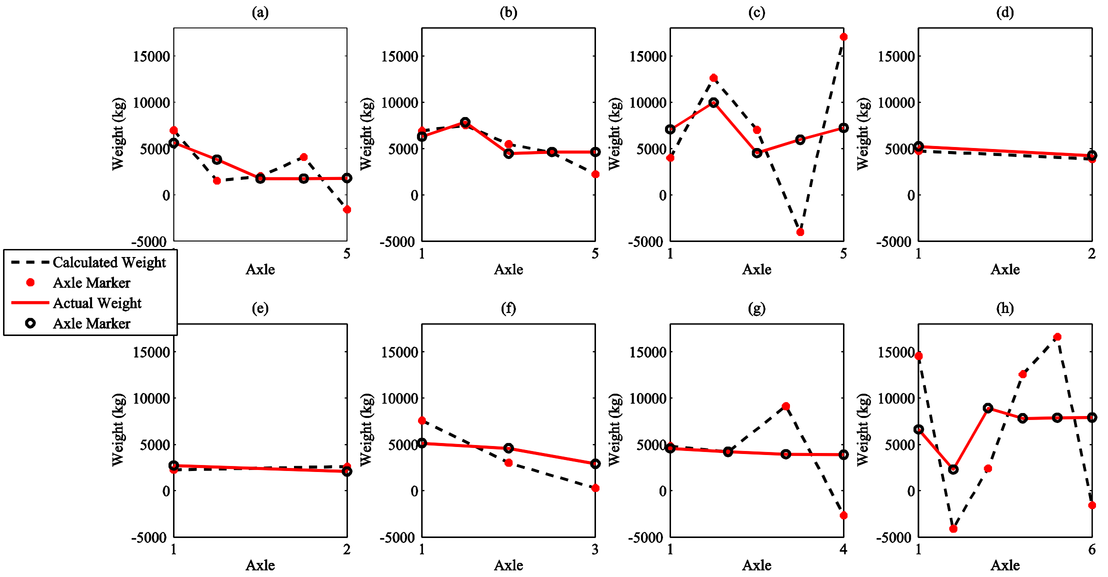

Figure 14 Calculated vs Actual Axle Weight

Table 2 Accuracy of cBWIM

Def. record used for:	Vehicle No.	No. of Axles	Gross Weight Error	Single Axle Weight Error	Group Axle Weight Error
I.L. Calibr-ation	1	5	-11.5%	42%	111%
	2	5	-4.1%	7%	25%
	3	5	5.7%	35%	119%
Testing	4	2	-9.3%	9%	-
	5	2	0.9%	21%	-
	6	3	-13.7%	48%	62%
	7	4	-6.9%	-	76%
	8	6	-2.3%	120%	136%

The results for all axle weights can be seen in Figure 15. This figure plots the mean error ± 1.96 standard deviations for each bridge length and for each of two scan rates: 120 Hz and 1000 Hz. (If the error is normally distributed, the mean ± 1.96 standard deviations gives the 95% confidence interval bounds). The error is defined here as,

$$\frac{(W_{BWIM} - W_{Actual})}{W_{Actual}} \times 100$$

where W_{Actual} and W_{BWIM} are the actual and BWIM axle weights respectively. Increasing the scan rate would be expected to reduce the influence of random noise in the measurements and therefore to improve accuracy. Figure 15 shows that this is indeed the case and that the low scan rate is a possible reason for the poor measurements of axle weights.

The trend in Figure 15 is that an increase in length leads to a decrease in the width of the 95% confidence interval and so better overall accuracy. The mean error is also improving slightly with span.

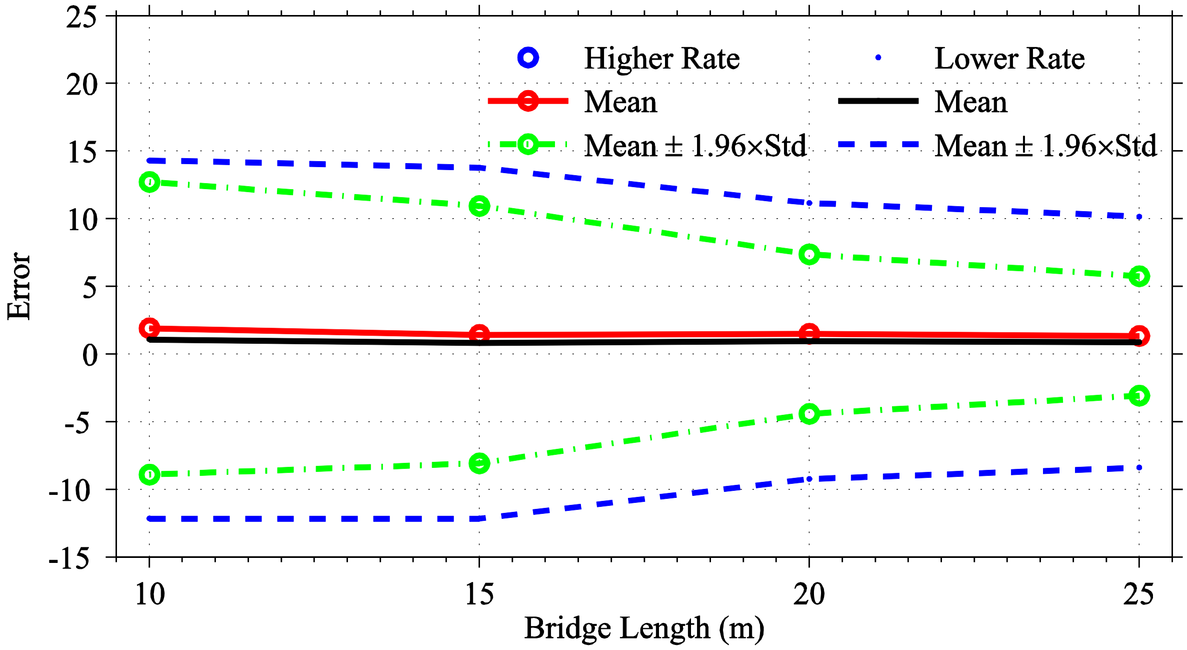

Figure 15 – Mean and 95% Confidence Interval of Error for two Scan Rates

Conclusions

The methods available for the measurement and monitoring of vehicle weights have evolved from the use of static weigh stations to on-road apparatus and bridges which allow the measurement of vehicle weights while they are in motion. Early BWIM systems with axle detectors are now being replaced with nothing-on-the-road systems. This paper takes the technology a step further: it presents a completely contactless BWIM system for which no contact is required between the sensors and the bridge. By its nature, such a system will need to be recalibrated using a truck of known weight, for each set up. It will therefore perhaps be best suited to short-time data collection; for example, alongside a bridge inspection or to collect samples of truck weights for a large number of locations in a secondary road network. There are very significant advantages for bridges where access is difficult or impossible.

The cBWIM system presented uses a low-cost digiscoping concept that utilizes an off-the-shelf telescope and camera. The accuracy achieved is at the low end of what is available in typical WIM systems. As would be expected from BWIM, the gross weight accuracy is better than the accuracies of groups and individual axle weights. It seems likely that accuracy will be improved in the near future by using more high-powered telescopes and/or higher camera scan rates. The cBWIM performed better on bridges of greater length. This could be due to the longer period of time the vehicle is on the bridge which would help to overcome inaccuracies due to dynamics. The signal to noise ratio may also be falling with increasing length as the same level of noise was assumed for all sensors, regardless of bridge length.

This paper provides a proof-of-concept for what is, to the authors' knowledge, the first of its kind, namely, an entirely contactless Bridge Weigh-in-Motion system.

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