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DEVELOPMENT OF A NOVEL BRIDGE WEIGH-IN-MOTION SYSTEM

Eugene J. O'Brien and Niall J. Kealy

ABSTRACT

A multiple equation B-WIM system is described which utilises data from strain gauges at a number of locations longitudinally along a bridge. Instantaneous calculation of axle and gross weights is shown to be theoretically possible provided the equations relating strains to weights are not dependent. This is shown to be possible for two-axle trucks in single-span bridges and for three-axle trucks in two-span bridges. A preliminary trial demonstrates some of the features of the system and is a useful indicator of where further research is needed. It is reported that further development and comprehensive testing is in progress.

INTRODUCTION

The principle of using a bridge as a scales for the weighing of trucks in motion was developed by Moses and others in the 1970's and 1980's (Moses 1979, Peters 1986). As illustrated in **Figure 1**, a Bridge WIM (B-WIM) system typically consists of strain sensors located underneath the bridge and a data-acquisition system capable of recording strain at high speed. In conventional B-WIM systems, axle detectors on the road surface are also used to determine the number of axles, their spacing and the truck speed. Axle detectors can take the form of pneumatic tubes, electrical contact switches or low-grade piezo-electric sensors.

The concept of B-WIM has considerable potential for accuracy as it makes possible the measurement of impact forces over more than one eigenperiod. As bridges are large, a great number of sensor readings can be recorded during the time it takes for a truck to cross. Full exploitation of this information can be used to gain information on the dynamic behaviour of the truck whose axle weights are being sought. This in turn can be used to obtain a more accurate estimate of the static axle weights. Alternative strategies being investigated in the European *WAVE* project (Jacob & O'Brien 1996) in 1997-1998 are the use of multiple bridge strain sensors (as described here) and the use of a combination of bridge and traditional pavement WIM sensors. A considerable research effort is also being expended on the development of more sophisticated dynamic models than those currently used.

THEORY OF MULTIPLE-EQUATION B-WIM SYSTEMS

This paper describes a method of improving the accuracy of B-WIM systems through the measurement of strain at more than one location longitudinally along the bridge in order to obtain more equations relating strain to axle weights. Conventional B-WIM systems involve the recording of strain at one longitudinal location only. The theoretical strain at such a location, A, is a function of the influence line and the axle weights:

$$\varepsilon_A^{TH}(x) = W_1 I_A(x) + W_2 I_A(x-L_1) + W_3 I_A(x-L_2) + \dots\dots\dots + W_n I_A(x-L_{n-1}) \qquad (1)$$

where:

$\varepsilon_A^{TH}(x)$ = theoretical strain at A when the first axle is at a distance x from the start of the bridge,
W_1, W_2,.........., W_n = axle weights,
n = number of axles,
$I_A(x)$ = influence function (strain at A due to unit load at a distance x from the start of the bridge) and,
L_1, L_2, ... L_{n-1} = distances of axle numbers 2, 3, ... n respectively from axle No. 1.

Strain is recorded at high frequency as a truck crosses the bridge and several equations of the form of equation (1) can be written. As there are generally more equations than unknown axle weights, the best-fit solution is generally chosen, i.e., the axle weights which minimise:

$$O = \sum_{i=1}^{m} \left\{ \varepsilon_A^{ME}(x_i) - \varepsilon_A^{TH}(x_i) \right\}^2 \qquad (2)$$

where:

O = objective function
m = number of measurements
$\varepsilon_A^{ME}(x_i)$ = measured strain when the first axle is at a distance x_i from the start of the bridge

Individual axle weights are summed to determine the gross vehicle weight. A major source of inaccuracy in B-WIM systems results from truck bouncing and rocking motions. Different forces are applied by an axle to the bridge when it is at different points along it. This affects the measured strains and is not accounted for in equation (1).

The problem of axle bouncing and rocking motions is addressed in this study through the use of measured strains at a number of different longitudinal locations along a bridge. If strain were measured at n different longitudinal locations and n independent equations of the form of equation (1) could be applied, then all n axle weights can be calculated for each value of x_i, i.e., an *instantaneous* calculation of axle weights would be possible. This would solve the problem of varying axle forces by providing a complete history of such forces as the truck crossed the bridge. Unfortunately, while it is possible to measure strain at many different longitudinal bridge locations, the resulting equations are not always independent.

Single-span bridge

A single-span simply supported bridge is considered first with two longitudinal sensor locations. The influence function for strain at a distance a from the start of such a bridge is given by:

$$I(x) = \begin{cases} \dfrac{a(l-x)}{EZl} & for\ a \le x \\ \dfrac{x(l-a)}{EZl} & for\ a > x \end{cases} \qquad (3)$$

where:

a = distance of strain gauge location from start of bridge,
l = span of bridge,
x = distance of unit load from start of bridge,
E = modulus of elasticity,
Z = section modulus (relating moment to stress).

If there are two longitudinal sensor locations, there will be two equations of the form of equation (1). For a two-axle truck, an instantaneous calculation can be carried out by substituting the measured strains for the theoretical to give:

$$\varepsilon_A^{ME}(x) = W_1 I_A(x) + W_2 I_A(x-L_1)$$

$$\varepsilon_B^{ME}(x) = W_1 I_B(x) + W_2 I_B(x-L_1)$$

These can be expressed in matrix form as:

$$\begin{Bmatrix} \varepsilon_A^{ME} \\ \varepsilon_B^{ME} \end{Bmatrix} = \begin{bmatrix} I_A(x) & I_A(x-L_1) \\ I_B(x) & I_B(x-L_1) \end{bmatrix} \begin{Bmatrix} W_1 \\ W_2 \end{Bmatrix} \tag{4}$$

Equations (4) can be solved for W_1 and W_2 if and only if the determinant of the matrix is non-zero, i.e., if $D \neq 0$ where:

$$D = I_A(x) I_B(x-L_1) - I_B(x) I_A(x-L_1) \tag{5}$$

When both axles are before the first sensor location or after the second sensor location, substitution of equation (3) into equations (5) gives a determinant of zero. Thus, the equations are dependent and an instantaneous calculation of axle weights is not possible. However, when both axles are between the sensors, equation (5) reduces to:

$$D = lL_1$$

where l is the bridge span length and L_1 is the length between the axles. This is clearly non-zero and an instantaneous calculation is indeed possible.

A simply supported bridge with three longitudinal sensor locations was also investigated. It was found that, for all possible truck locations, two of the equations were dependent. Thus, for a simply supported bridge, only two independent equations are possible and simultaneous calculation of axle weights is only possible for 2-axle trucks.

Two-span bridge

A two-span bridge with two equal spans was also investigated. Five possible longitudinal sensor locations were considered in total as illustrated in Fig. 2. The five corresponding influence lines are also illustrated in the figure.

Different combinations of the influence functions were found to be dependent in different parts of the bridge. This is illustrated schematically in Fig. 3. The curves in this figure indicate the dependencies between influence functions. For example, for an axle in part AB of the bridge, the influence functions for sensor numbers 1 and 2 are dependent and those for sensor numbers 3, 4 and 5 are dependent. This leaves only two independent equations for this part of the bridge. Fortunately, there are two parts of the bridge, BC and EF, where three independent equations exist. In these parts, an instantaneous calculation of axle weights is possible for trucks with up to three axles. If it is assumed that individual axles within tandems or tridems are of equal weight, then three independent equations is enough to make instantaneous calculations possible for most truck types. For a particular example, the determinant of the matrix of three equations was calculated for a range of positions between B and C. It was found that, if a small error existed in the calculated vehicle speed or axle spacing, the determinant varied significantly and approached zero at one point within the region. However through most of the region, the determinant was non-zero and the equations were independent.

PRELIMINARY EXPERIMENTAL VERIFICATION

A preliminary test has been completed of a multiple-equation B-WIM system using the Belleville Bridge on the A31 motorway near Nancy in France. This bridge is a two-span composite box girder consisting of a single steel box and a concrete slab. It is adjacent to the COST 323 (Jacob 1994) Continental Motorway Test where two B-WIM systems and six pavement WIM systems are being tested in 1997/98. Because of the proximity to the test site, it is possible to identify trucks on the bridge that have been selected from the general traffic flow by the police and pre-weighed statically.

As illustrated in **Fig. 4**, strain gauges were installed at three longitudinal locations corresponding to sensor numbers 1, 2 and 3 in Fig. 2. Instantaneous calculation of axle weights were carried out when trucks were between mid-way and ¾-way across the left span (part BC in Fig. 2). At each longitudinal sensor location, active electrical resistance strain gauges were attached to longitudinal stiffeners at two points transversely on the bottom surface on the inside of the box.

Axle detectors are used in conventional B-WIM systems to identify the location of the truck, its speed and the numbers and spacing of axles. Low grade piezo-electric bars were installed at the end of the Belleville bridge for axle detection purposes. However, at the time of the preliminary trials, they were malfunctioning. As a result, axle spacings were measured manually on the stationary trucks while they were being weighed statically and the speed of each truck on the bridge was determined using a hand-held laser device. The synchronisation of the measured strain records with the theoretical calculation requires a knowledge of the time that the truck reaches the start of the bridge. This was estimated from a video record of the traffic.

Pre-weighed data for six vehicles was collected. One of these was selected at random as a calibration vehicle and the remaining five used to carry out the preliminary test. One run of one truck is clearly inadequate for normal calibration purposes but was considered sufficient for the purposes of a preliminary trial. Comprehensive testing of the system is planned in late Spring 1998 for which calibration in accordance with the COST 323 specification (COST 323 1997) will be carried out. Piezo-electric axle detectors will be used for this test to improve the synchronisation of the measured strain records with the theoretical calculation.

A typical result from the preliminary trial for gross vehicle weight is illustrated in **Fig. 5**. In the region between 33 m and 37 m from the start of the bridge, the determinant of the matrix of equations was small and the calculated gross vehicle weights approached infinity. Outside of this region, it can be seen that the errors vary considerably, particularly in the left portion of the graph. It is unlikely that this variation is due to the dynamic movements of the truck although this would be expected to be a contributory factor. It is more likely that there are substantial errors due to inaccuracies in the synchronisation of measured with theoretical results. This and a relatively low resolution in the strain readings would lead to errors which would be exasperated by a near-zero determinant. The relatively low variation in results on the right hand side of the graph may be due to larger values of the determinant. It is not clear why there is an apparent bias which is different in the different parts of the graph. Despite the great deviation in calculated gross weights from the static value, the calculated mean gross weight from all the instantaneous values is relatively accurate.

Fig. 6 provides a comparison of the result for the multiple equation B-WIM system with results calculated using the conventional B-WIM algorithm. Gross weights were calculated separately using data from each of the three longitudinal sensor locations. In addition, the mean of the three is presented. It can be seen that, except for strain gauge No. 3 (near central support), the multiple equation B-WIM system is more accurate than the conventional B-WIM system. This result is typical of the five trucks for which data was available. The reason for the high accuracy of results from gauge No. 3 is not clear at this time although it is significant that the strain resolution at this location was the highest for all locations. The gross weight calculated using gauge No. 3 was higher than the multiple equation system in three cases, similar in one and less high in one other.

CONCLUSIONS

The multiple equation B-WIM system is shown to be theoretically possible for two-axle trucks on single-span bridges. For two-span bridges the parts of the bridge for which instantaneous calculations are possible for three-axle trucks are identified. A preliminary gives some indication of the type of results that can be expected. It is anticipated that significant improvements will be achieved in comprehensive trials to be undertaken in Spring 1998.

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ACKNOWLEDGEMENT

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AUTHOR BIOGRAPHIES

Eugene O'Brien is vice-chairperson of the European research action, COST 323 (weigh-in-motion of road vehicles) and chairs the Bridge Applications of WIM subcommittee. He is also chairperson of the Scientific and Technical committee of the European Commission *WAVE* project and is chairing the International Scientific Committee for the 2nd European conference on WIM to be held in Lisbon in September 1998. He lectures at Trinity College Dublin, Ireland.

Niall Kealy has obtained Bachelors and Masters degrees in Civil Engineering from Trinity College Dublin specialising in Bridge weigh-in-motion. He is currently working as a project manager with N.J. O'Gorman and Associates.

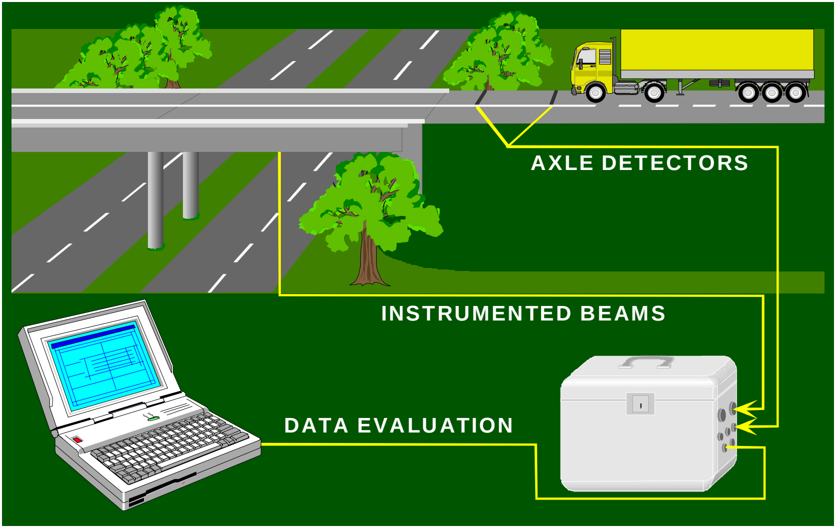

Figure 1 - Schematic of conventional B-WIM system (after Znidaric et al. 1996)

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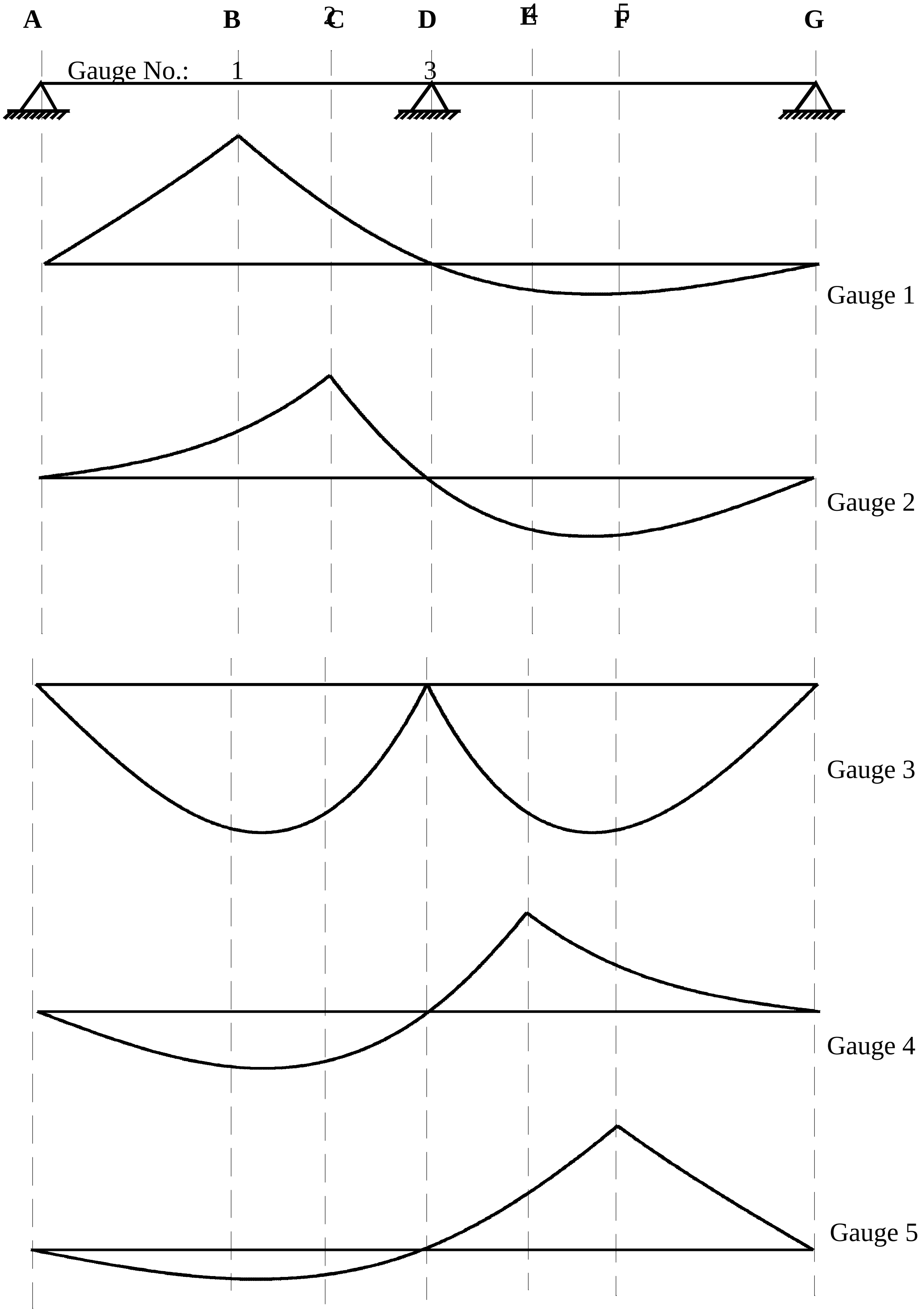

Figure 2 - Longitudinal sensor locations and corresponding influence lines

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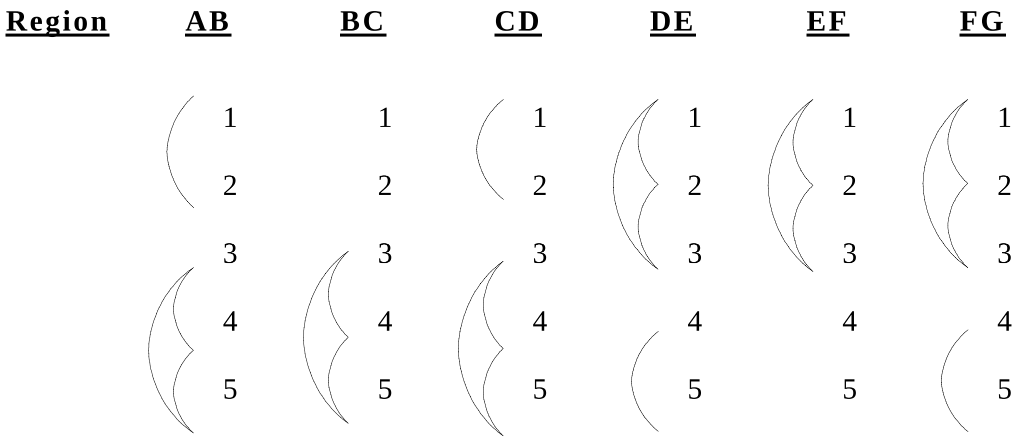

Figure 3 - Dependency of influence functions

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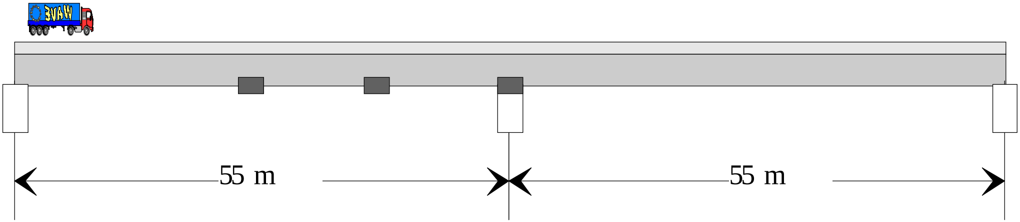

Figure 4 - Belleville bridge and strain gauge locations

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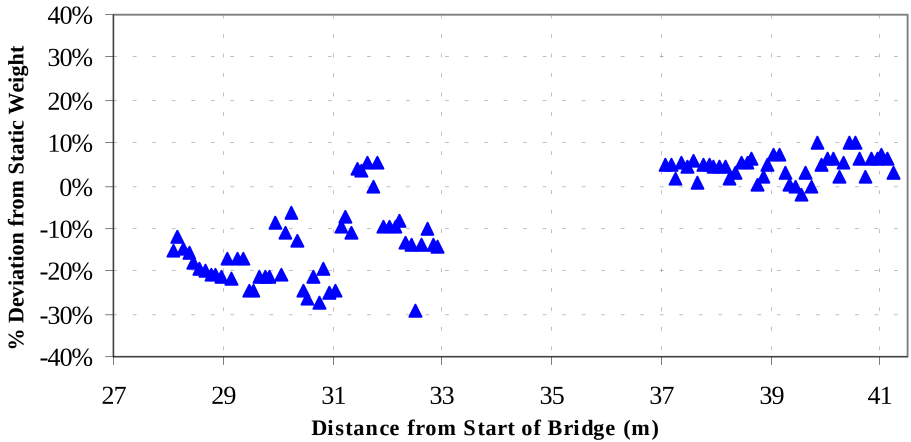

Figure 5 - Errors in calculated gross vehicle weight versus distance

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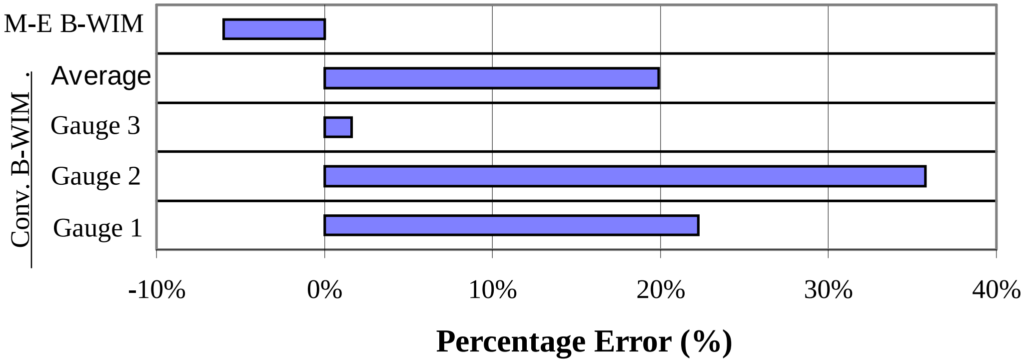

Figure 6 - Comparison of results from multiple-equation (M-E) B-WIM and conventional B-WIM algorithms

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