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Recent Developments in Bridge Weigh in Motion (B-WIM)

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Abstract

Bridge Weigh in Motion (B-WIM) uses advanced sensing systems to transform existing bridges into a mechanism to determine actual traffic loading. This information on traffic loading can enable efficient and economical management of transport networks and is becoming a valuable tool for bridge assessments and damage detection. B-WIM can provide site specific traffic loading on deteriorating bridges, which can be used to determine if the reduced capacity is still sufficient to allow the structure to remain operational and minimise unnecessary replacement or rehabilitation costs and prevent disruption to traffic. There have been numerous reports on the accuracy classifications of existing B-WIM installations and some common issues have emerged. This paper details some of the recent developments in B-WIM which were aimed at overcoming these issues. A new system has been developed at Queens University Belfast using fibre optic sensors to provide accurate axle detection and improved accuracy. The results presented in this paper show that the fibre optic system provided much more accurate results than conventional WIM systems, as the FOS provide clearer signals at high scanning rates which require less filtering and less post processing. A major disadvantage of existing B-WIM systems is the inability to deal with more than one vehicle on the bridge at the same time; sensor strips have been proposed to overcome this issue. A bridge can be considered safe if the probability that load exceeds resistance is acceptably low, hence B-WIM information from advanced sensors can provide confidence in our ageing structures

1 Introduction

In Europe, and many other parts of the world, bridges are a vital part of our ageing infrastructure, a recent European survey [1] found that the majority of bridges, in the survey, were built in the post war period from 1945 to 1965. Many of the bridges have showed substantial deterioration due to increased loading and adverse environmental conditions. The current loading on these bridges is now significantly different to the service loads at the time of design and construction. It is predicted that this situation may worsen and without adequate Structural Health Monitoring (SHM) bridges will need increasingly more maintenance, major rehabilitation or unnecessary replacement in the near future. Hence, information on the status of our bridge stock is vital for the provision of safe infrastructure to facilitate growing intra-EU and global trading. As the loading is highly variable from site to site, most assessment ratings of bridges tend to be inaccurate. This leads to excessive conservatism in some instances, that is, bridges can be recommended for unnecessary and costly repair, but dangerous over-estimates of bridge safety in other instances. A site-specific assessment based on real traffic loading on the structure reduces the degree of conservatism while ensuring the safety of the structure. This type of assessment can enable efficient and economical management of transport networks, leading to considerable savings in maintaining our infrastructure. [2]

In recent years, SHM systems have been developed to monitor bridge safety. However, these systems are not an accurate representation of the overall safety of a bridge. A road bridge is only safe if the stresses caused by the passing traffic are less than the capacity of the bridge to resist them. Conventional SHM systems can be used to improve knowledge of the bridge capacity to resist stresses but give no information on the causes of increased stresses. The solution to the bridge safety problem is considered as two-fold; firstly, the safety and assessment monitoring and, secondly, the control and measurement of overloaded trucks or truck capacity that can cause further damage to a deteriorated bridge.

A bridge weigh in motion (B-WIM) system uses the measurement of a deformation of a bridge, under live loading, to estimate the characteristics of passing traffic loads. The main advantage of the system is its non-destructive implementation and its ability to provide completely unbiased traffic data. An existing bridge is instrumented with a series of strain sensors which are positioned and installed on the bridge soffit. The system uses the full bridge as a weighing mechanism and can provide accurate gross weights of vehicles passing over the bridge. First introduced in by Moses in the 1970's the system consists of two elements one to measure a varying property of the bridge, usually strain, and one to detect axles [3]. The information provided by these elements, ie measured strain, is then converted into axle weights through the application of an algorithm, usually some variation of the Moses algorithm. The Moses algorithm assumes that the bending in the bridge (Mth) is proportionate to the product of the magnitude of the applied moving load (W) and the influence line of the bridge (I). Fig 1 shows the general concept and arrangement of a B-WIM system.

B-WIM systems have the potential to provide an inexpensive and, if needed, portable method of rapidly retrieving traffic data. In recent decades both industry and researchers have sought to develop B-WIM system which can provide at least 95% accuracy in GVW. The deployment of such a system would be desirable as it would enable direct enforcement of overloaded vehicles and the collection of data for planning and economic surveys. Various B-

WIM methods exist for calculating GVW and Section 3.2 in this paper provides information on the accuracy of three B-WIM methods which were calibrated on a slab and girder bridge in Winnipeg, Canada.

Extensive work has been carried out on the development of the theoretical models for B-WIM and the research demonstrates that Tikhonov Regularisation can be used to improve ill conditioned Moses equations which occur when axles are closely spaced relative to the bridge span [5]. More recently Moving Force Identification (MFI) techniques have been applied to measured signals to improve the accuracy of the measured axle weights [6]. These techniques have been found to improve the accuracy of the systems but a report on the accuracy classification of several B-WIM installations found that current accuracy levels are sufficient for selecting vehicles to be weighed using static scales, but insufficient for direct enforcement [7]. The report detailed the improved accuracy of existing B-WIM systems due to data processing and sensor placement and better site selection. Accuracy classification is determined using the standard set out in COST 323 (1999), six accuracy classes were defined with A (5) being the most accurate and E being the lowest class with accuracy of less than 25% (Jacob et al.1999). Classes A (5) and B+(7) are required for direct legal enforcement and B (10) and C(15) are sufficient for pre-selection of overloaded vehicles, classes below this are generally used for traffic evaluation.

Schmitt [9] has provided a review of existing B-WIM sites in France; the research covered a wide range of field tests. The paper highlights the difficulty in obtaining accurate results in multiple presence situations and that overload screening could not be achieved in slightly skewed bridges due to inaccuracies. Pre-stressed concrete bridges were not considered in this study due to the incorrect perception that there is low sensitivity to axle and single vehicle loads in this type of bridge. This research highlighted the gaps in B-WIM research knowledge and as a high proportion of the global bridge stock are skewed and pre-stressed concrete the application of B-WIM systems would be limited if either of these bridge types were deemed unsuitable.

To provide a full set of results a B-WIM system requires an accurate method of axle detection. It is widely recognised that any form of axle detector on the road surface is not ideal for B-WIM applications as it can cause disruption to the traffic [10]– [12]. The earlier research on axle detection for B-WIM used road surface sensors but the longevity of the overall system is compromised as the detectors are damaged by heavy traffic. Ideally a nothing on the road (NOR) system should be implemented, this method has been proven to be successful in some structures ideally thin slab bridges [13]. However, for beam and slab bridges the peaks can be confused with other peaks such as those caused by vehicle or bridge vibration [14].

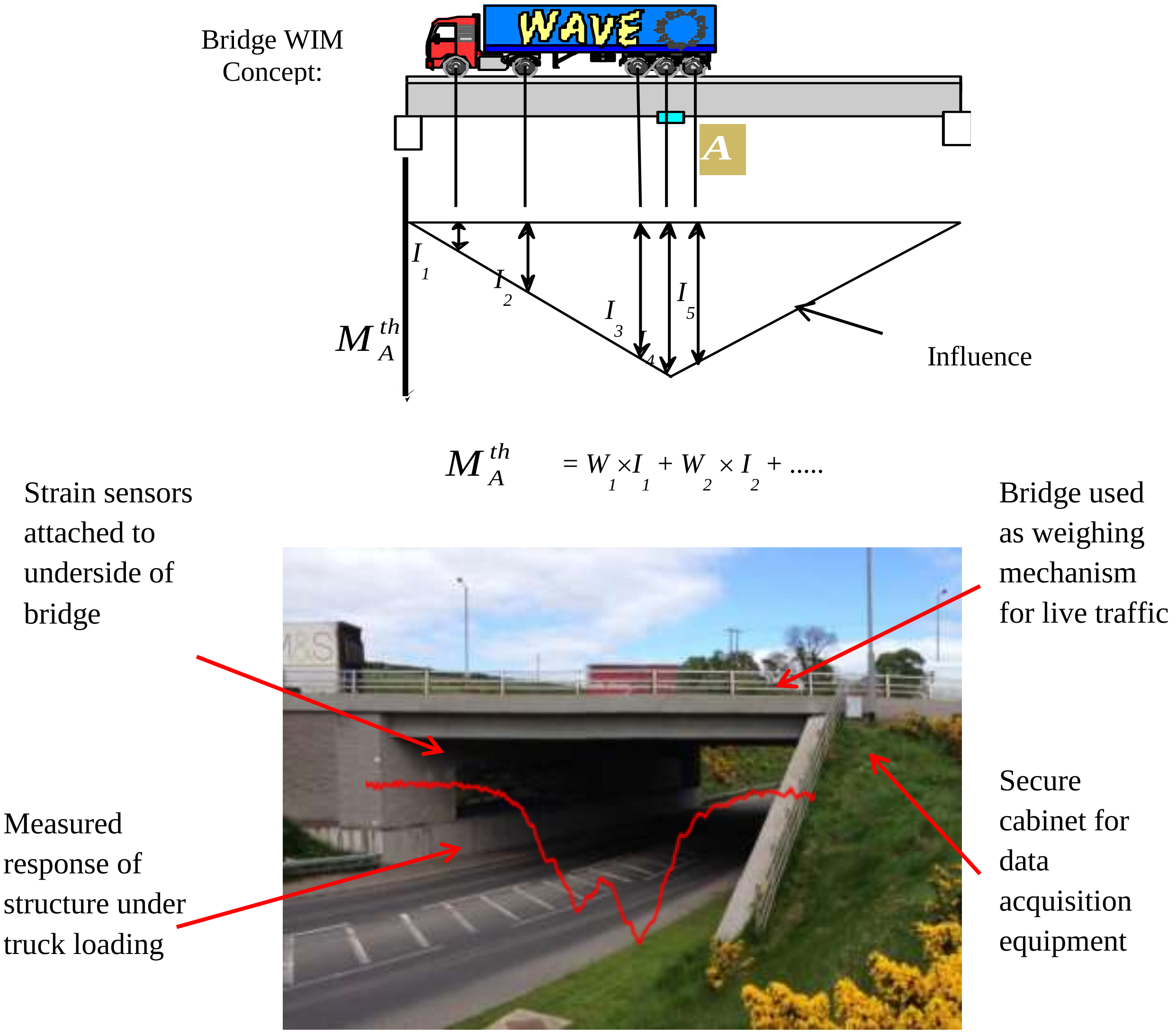
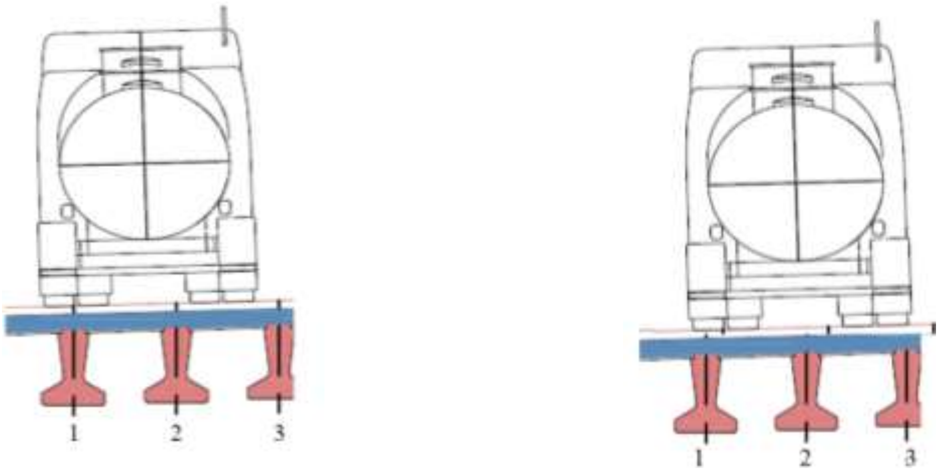


Fig 1 General B-WIM concept and arrangement [4]

If the axle detecting sensor is attached to the underside of the slab clear peaks can be obtained, but the strains in the slab are sensitive to transverse location of the wheel in relation to the sensor. In the case of beam and slab construction the overall stiffness of the structure is higher and a passing axle causes only local effects in the transverse direction. For the vehicle shown in fig. 2 (a), peak changes in transverse strain in the deck can be measured between beam 2 and 3, however,if the location of the truck was varied slightly in the transverse direction as shown in fig. 2 (b) clear peak changes in strain would not occur. Further issues with the sensitivity of axle detection emerged in an investigation with the use of a B-WIM system in the Millau Viaduct [15], as described in section 3. In order to overcome this existing shortfall, new strategies for axle detection are being investigated. This includes the use of vision systems [16] and the development of a new shear strain sensor, and alternative sensor locations on the supporting beams are investigated as solution to the current axle detection concern[14].



(a) Wheel loading between beam 2 and 3 (b) Wheel loading directly over beam

Fig 2 Varying transverse location of vehicle in the lane.

Another issue, which can have considerable effects on the accuracy of a B-WIM system is the multiple-presence of heavy vehicles on the bridge where there is more than one lane travelling in each direction. Traditionally the gross vehicle weight of the vehicle is determined by the global response of the structure to all of the vehicles crossing the bridge. If all heavy vehicles used the first lane this does not cause an issue as each vehicle would have an individual effect on the structure. The problem arises when two heavy vehicles cross the structure side by side and structure responds to the combined load of both vehicles. A proposed solution is to use an influence surface, as opposed to an influence line, in the algorithm [17]. Theoretically this would provide a solution but the calculation required can be extremely demanding and the calibration of such a system can be labour intensive and time consuming. An alternative method is to use strip sensors to mitigate this MP problem in B-WIM systems [18].

B-WIM data has the potential to provide valuable information for the development of bridge and traffic analysis procedures and has recently been used in numerous applications. The information collected from various B-WIM sites throughout the world, particularly in Europe, is now used to gain a clearer understanding of bridge dynamics and develop accurate assessment methods which can be applied to individual site-specific conditions.

1 Theoretical Developments

1.1 Improvements in the B-WIM algorithm

The Moses algorithm forms the basis of most B-WIM post processing procedures. It is based on the fact that the measured change in strain recorded at a sensor (ε_j) is related to the bending moment (M_j), given by the following equation:

Where

E is the modulus of elasticity of the bridge material and S is the section modulus of the ith girder.

$$M = ES_i\varepsilon_i$$

The one-dimensional approach adopted by Moses means that the total bending moment is given by summing the strain sensors at that longitudinal location, usually midspan, if E and S_j are assumed to be constants then:

$$M = ES \sum_{i=1}^{no\_girders} \varepsilon_i$$

the product of the two constants ES is directly related to the total bending moment and the measured strain. Theoretically these constants can be determined from the bridge dimensions and material properties, however, in practice this is generally derived by the direct measurement of the effect of a vehicle of known load crossing the bridge.

The analysis is inverse type problem, the response of the structure is recorded as a change in strain and the live load causing this strain must be calculated. In order to do this the system is calibrated using a pre-weighed truck load, the influence line is then calculated and subsequent loads are calculated by utilizing the fact that the strain induced on the structure is proportionate to the product of the influence ordinate (I) and the magnitude of the load.

The number of unknowns is dependent on the number of axles (N) and the axle spacing in terms of number of scans C_1 to C_N is also required, calculated by means of the following equation:

$$C_i = (L_i x f)/v$$

Where L is axle distance in meters, f is the scanning frequency, v is the velocity and $C_1 = 0$

For any location of the first axle at scan number k the theoretical static response (M_k^T) can then be expressed as:

$$M_k^T = A_1 I_{K-C_1} + A_2 I_{K-C_2} \ldots\ldots + A_N I_{K-C_1+\cdots+C_N} = \sum_{i=1}^{N} A_i I_{(K-\sum_{j=1}^{i} C_j)}$$

in a real bridge the response is not static and the influence of the dynamic oscillation about the static response must be filtered out. A large number of measurements are available for each truck crossing, Moses used this fact to smooth out the dynamic component. This is done using a least squares method, the sum of the squares of the differences between the measured strain $M^M$and the theoretical $M^T$is minimised using the error function E[3] [19].

$$E = \sum_{k=1}^{K} [M_k^M - M_k^T]^2$$

As the GVW is then calculated from summing the axle weights the accuracy of the system is highly dependent on accurate axle detection and velocity calculation, hence the importance of a good axle detection method.

Since the 1970's there has been extensive improvements in the accuracy of B-WIM, one of the main reasons for this development is due to advances in computer technology and capability. The original Moses algorithm is not suitable in a multiple-presence situation it is designed to work when there is only one truck on the bridge at any time as the equations are liable to become ill-conditioned when there is more than one truck present. The introduction of the 'Moving Force Identification (MFI) theory accelerated the success and accuracy of the B-WIM system, MFI theory helped to reduce the dynamic uncertainty associated with B-WIM measurements[20]. Thus, increasing the accuracy of the B-WIM calculations compared to the static algorithm method that was previously used. The accuracy can be further improved when MFI combined with Tikhonov regularization and with proper location of sensors the transverse position of the vehicle can be detected. Field trials indicate when the method was applied it filtered the results from a B-WIM acquisition system and axles were more clearly detected. However, when the results were filtered errors from the original data were magnified therefore an accurate axle count could not be provided. In general for the detected axles the method provides relatively accurate results however, for the first axle the inaccuracies were as high at 17% [5].

Further analytical developments include the application of a technique called the Wavelet Theory which is used in conjunction with the results from the strain sensors. A wavelet transform was used in the data acquisition to produce a set of results from the sensors which are installed on the underside of the bridge[12]. The wavelet transform has been tested using a NOR system, firstly a 2D model was used to generate the strain signals to test the wavelet, very accurate results on velocity and axle spacing and detection were achieved. The wavelet was then used on results generated from a real bridge in Slovenia, the strain results that were obtained were put through a series of wavelet approaches, each approach scaled the results differently and determined different peaks. The reverse biothogonal wavelet scaled the results and showed five distinct peaks representing axles as shown in Fig 3. In general, the wavelet produces accurate results in axle detection and spacing but if errors exist in the original data they are then magnified in the wavelet results.

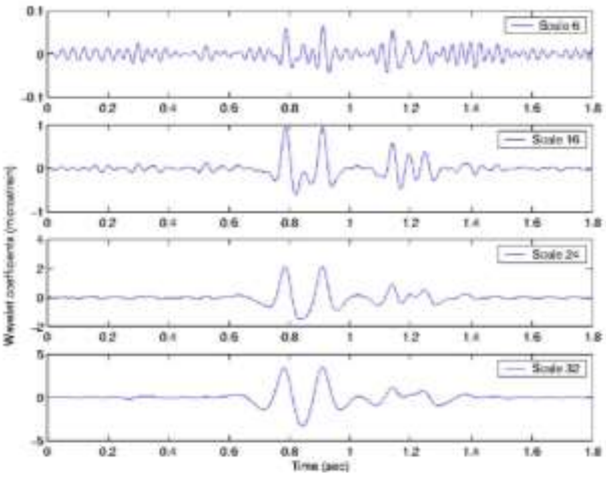


Fig 3 Wavelet detection results [12]

Recently a new method of filtering the strain signal was investigated by [21] the aim was to improve the accuracy in detecting gross vehicle weights (GVW) and individual axle weights. The commercial system SiWIM was used to measure the strain response of a bridge to moving traffic and a finite element model (FEM) was used to predict the response. A filter was applied to the measured strain signal in order to remove some of the dynamic effects. It was determined that the moment from the B-WIM testing was taken from the following equation:

$$M^{WIM} = M^{Load} + M^{Vibration} + M^{Stiffness} + M^{Boundry} + M^{Time}$$

Where M^{Load} was the moment effect from the loads, $M^{Vibration}$ was moment effect from the vibration of the structure, $M^{Stiffness}$ was moment effect from the elastic stiffness, $M^{Boundary}$ was moment effect from the boundary conditions, and M^{Time} was moment effect from time delay.

The applied wheel load will cause free vibration in the structure, the FEM showed that vibrations occur in both the transverse and longitudinal directions. Once the vibration effect was determined, it was filtered from the overall strain signal. It is known that the bridge stiffness can change with age and non-destructive tests (NDT) can be used in order to determine the current elastic stiffness, which then allowed for the stiffness effect to be accounted for in the signal. Various boundary conditions were modelled to determine the effect on the strain signal; this simulated strain effect was taken from the real strain signal in order to filter the results. The time delay effect was measured as it would take some time for the energy to transfer from the wheel load to the sensor location. Therefore, the dynamic force simulations would be different to the static force simulations. The time distance needs to be adjusted to properly fit the strains from the sensors. After the filtering was applied the signal represents the true static response of the structure which was then used for the weight calculation. This new filtered algorithm provides improved predictions in both single axle weights and GVW

1.2 Assessment of methods for accurate measurement of GVW

Accurate measurement of GVW can provide a valuable tool for bridge design; it provides an efficient design method which is based on real traffic loads. Various B-WIM methods exist for calculating GVW. A case study carried out on a 7 span slab and girder bridge in Winnipeg, Canada provides information of the accuracy of three B-WIM methods [22], all three methods use NOR axle detection. The first method, the 'Asymmetry coefficient method', was developed by one of the authors [23] and assumes that the total load of a truck GVW is a uniformly distributed load on a fraction of the bridge span. The method used asymmetry in the shape of the bending moment diagram to calculate the gross vehicle weight. The study found that in many cases the method provided inconstant results and the deviation from the measured GVW was quite large, in one case a negative value for GVW was obtained. The second method was also developed by the authors and is referred to as 'The Two-Station Method', in this case the truck load was again represented by a UDL, and the GVW was calculated from the girder responses at two instrumented transverse locations, near the first quarter span and the second third span approximately. This method provided better results particularly for the shorter vehicles, and the maximum average standard deviation of

4.5% from the measured GVW. However, the accuracy reduced as the truck length increased and for the longer vehicle of 21.76m (almost double the length of the shorter vehicle) the average error deviation was 9.8% to 21.5%. It was found that the two-station method provided good results when the length of the truck was less than half the length of the bridge. The third method used a strain signal area to calculate the GVW using the Beta method developed by Ojio and Yamada [10]. As with the previous methods this system was calibrated using a truck with known GVW (GVWc), when this truck passes over the bridge an influence area was obtained (Ac). The influence area was then calculated when subsequent trucks pass over the bridge (A), the unknown GVW of the trucks was then calculated using the following equation:

$$GVW = \frac{A}{Ac}.GVWc$$

Using this beta method, the speed of the vehicle was calculated from peak strains at different longitudinal locations on the structure. A direct vehicle velocity was calculated by dividing the distance between the two locations by the time interval between the corresponding peaks, thus allowing more accurate calculation of GVW. If accurate vehicle speeds are obtained the beta method has the potential to provide constant measurements, with errors <5% of the GVW.

2 Advances in sensing technology for B-WIM

2.1 Existing Sensor Technology

A B-WIM system is normally composed of bridge sensors to measure strain, axle detecting sensors, data acquisition systems and computer. In most systems, electrical resistance strain (ERS) gauges are used to measure bridge strain, this is a bonded metallic strain gauge. The gauge commonly consists of a metallic foil in a grid pattern and the electrical resistance of the gauge varies in proportion to the applied strain. In practice, the strain measured is very low, therefore the gauges are usually applied in a Wheatstone bridge configuration to amplify. Strain gauges can be active in one, two or four arms of the Wheatstone bridge and the remaining positions are filled with fixed resisters. The sensitivity of the gauge is increased relative to the number of strain gauges made active. The strain gauges can be bonded directly onto the bridge structure or fixed using a strain transducer, the latter being more favourable as it allows for sensors to be reused. A recent review of installed B-WIM systems, using ERS gauges, found that the accuracies achieved were not sufficient for enforcement of overloaded vehicles [7]. Indicating alternative methods of strain measurement are required to evolve the B-WIM system beyond a pre-selection tool. A further issue with ERS B-WIM systems is the wiring effort required to connect all of the sensors to a control cabinet and the power consumption of such systems can limit the monitoring period on rural sites.

2.2 Optical sensors

Optical sensors, such as Fibre Bragg gratings (FBGs), are now well established for the measurement of strain, temperature, pressure and acceleration. The sensing signals from FBG’s are reflected changes in light wavelength (1nm shift equate to ~1.1$\mu\varepsilon$) making them well suited to multiplexing thus enabling measurements of multiple sensors along a single cable. FBG strain sensors show advantages over other commercially available strain sensors due to the intensity-independence of the measurement signal and the ability to keep accuracy while interrogating the signal at exceptionally high scanning rates (up to 2KHz). Furthermore, FBGs are small and lightweight, electrically passive, immune to electromagnetic interference (EMI) and have excellent resistance to corrosion. An additional advantage is the ability to combine FBG's to compensate for temperature induced strain changes. The key feature of a suitable FOS is to discriminate between strain and temperature thus providing accurate strain data while providing enhanced mechanical resilience during installation and in use measurement.

2.3 Application of FBG's to traffic loading

FBG'S are well established in the area of structural health monitoring due to their long- term stability and ease of fixing. To date the FBGs have not been established in B-WIM but have been used for the identification of equivalent traffic loads on a bridge [24]. The bridge selected for monitoring connects the harbour and highway in northern Taiwan. This bridge was chosen as it had a restriction on the maximum GVW of 25t due to deterioration. The 18 FBG gauges were installed on 5 beams of the 24m span RC bridge and 6 months of data was collected. The system was calibrated by determining the strain value excited on the structure by a calibration truck with a GVW 20t and the response of each subsequent vehicle crossing was then compared to this base signal to determine if the truck was above the maximum permitted weight. During the calibration, numerous loading runs were carried out with varying conditions such as changing the speed of the truck. The effect of reducing the speed of the truck from 40km/hr to 20 km/hr increased the measured strain by approximately 7με, and the average of the two responses was taken as a representative value at 185με. Given that the accuracy of the gauge was 1με this provided accuracy in weights of about +-108kg. The study was just a preliminary investigation and a full B-WIM system was not installed but the testing clearly demonstrated that FBG sensors have the potential to provide accurate data for such a system.

3 New strategies for axle detection

3.1 Post processing adjustments

In order to improve the accuracy of the system installed on the Millau viaduct a signal analysis method was used to identify the useful signals for axle load detection [15]. Statistical classification algorithms were used to classify the signal into three classes: the clean signal class, slightly noisy signal class and strongly noisy signal class. A five-axle truck was used as the model for the classification map, the classification output subsequently was used to determine information on the transverse location of the truck. There was an insufficient number of axle detection sensors included in the B-WIM system, as it was found the effects of the axle loads were local. Hence, when the wheel was not directly over the sensor, the signal was dominated by noise. This reduced the number of signals in the clean signal class.

However, axle loads were determined from the data collected from the clean signals and the accuracy was improved from Class D+ (20) to Class C (15).

3.2 Axle detection using vision systems

Current NOR axle detecting systems do not always provide clear identification of axle configurations due to the type of structure or the transverse position of the load. A new technique of axle detection was investigated using vision based methods by Caprani [16]. This method has the potential to provide axle configurations without disrupting the flow of traffic by using a road side camera system placed perpendicular to the traffic flow. The system was investigated for the analysis of congested traffic and it was found to be a viable tool for gathering inter-vehicle gap data. The locations of bumpers and axles present in traffic are provided by a vision system which was placed perpendicular to the flow of traffic. In congested traffic the determination of gap distance was relatively simple, a background extraction method was adopted [25]. An image of the site with no vehicles was used as a "background" image. The background is image was then subtracted from subsequent images of the site; a new image was then produced leaving only the areas containing a new object such as a vehicle. However, the relation to the background image can be effected by sudden changes in illumination conditions. The RGB (model that defines colour in terms of intensity of red, green and blue) modifies colour characteristics of the background image, hence this method would not be ideal under varying weather conditions. However, experimental laboratory testing has proven traffic analysis is possible with this method in a fully controlled environment [26].

For vision systems to be applied to a WIM system the information obtained from the wheel detection methods was most useful, this task was not so straightforward. Two methods were adopted, the Hough method and the template method. The Hough transform algorithm was widely used for traffic applications and therefore did not require any adaption. However, previous research has shown that accurate detection rates were highly dependent on the lighting conditions and frequent false positive wheels were detected.[27]. As the template method is mainly used for non-traffic applications the algorithm was modified to allow for wheel detection. [28].

Caprani [16] assessed the efficiency of each method for accurate axle detection; both of the algorithms are applied 50 images of two- axle vehicles (total of 100 wheels). The results are shown in below in Table 1

Table 1 Method Efficiency [16]

Method:	Wheels Detected	Wheels Missed	False Positives	Vehicles Correct
Template method	70	30	15	46%
Hough Transform	48	52	62	18%

The results show both methods are subject to high occurrences of false positives. A two-axle vehicle would be generally deemed as an easier vehicle for axle detection and as the results are largely unsatisfactory for this type of vehicle it can easily be determined that this method of analysis is not a viable tool for axle detection particularly when considering groups of closely spaced wheels.

3.3 Axle detection using a shear strain sensor

NOR axle detection methods identify axles as peaks in a strain signal; this strain measurement is commonly taken from a sensor located on the slab near the quarter points of a simply supported span. However, in the case of beam and slab bridges the strains in the slab are sensitive to the transverse location of the vehicle on the structure. If the wheel passes directly over the beam as shown in Fig 2 (b) then this can cause little or no strain in the mid region of the slab between the beams. In order to overcome this issue a numerical investigation to test the concept of using a shear strain sensor on the beams to detect axles was carried out [14]. For this research, a simply supported beam and slab bridge with a span of 30m was modelled and a simplified knife edge load of magnitude 10kN/m (900kN in total) was applied. The results indicate that as a 900kN load passes a change in strain of 26 micro strain is detected which is a very significant peak. The preliminary recommendation from this research suggest that when the transverse position of the vehicle is such that the wheel load occurs over the beams axle detection could be obtained from a sensor located at the interface of the web and flange as shown in Fig 4.

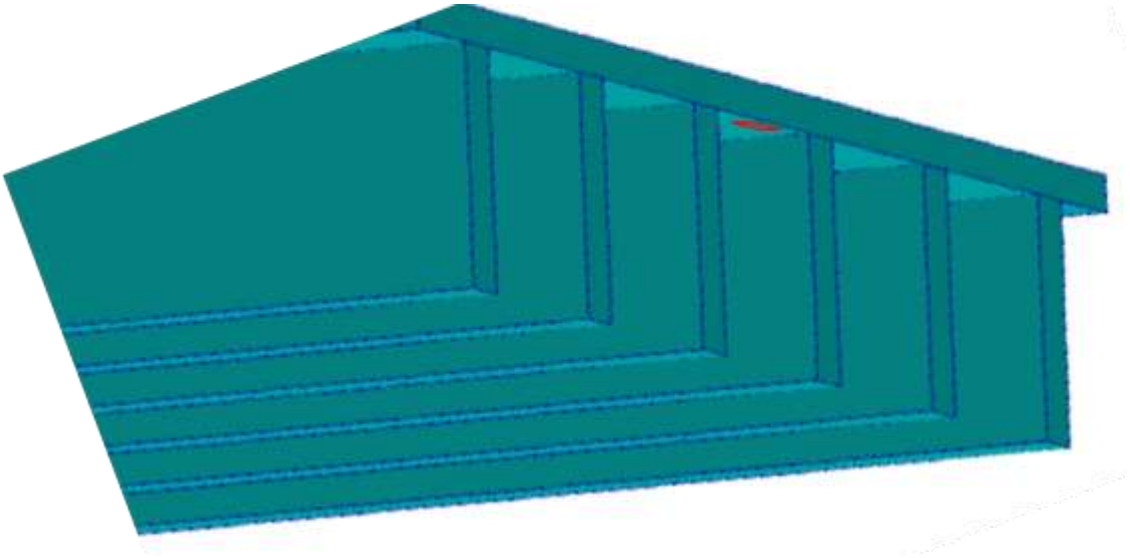


Fig 4 Recommended sensor location [14]

4 A solution to the multiple-presence problem

The original Moses algorithm used for B-WIM calculates axle weights from the global response of the structure to all vehicles crossing at one time, if the vehicles are travelling along one lane there is no issue. However, if two vehicles in adjacent lanes travel side by side near the centre span the algorithm has difficulty dividing the global response of the individual vehicles. One solution to this problem was to use an influence surface rather than an influence line [17]. This can eliminate the multiple presence issue, instead of using a single influence line the algorithm uses a 2D influence surface, the 2D algorithm enables the identification of the lane in which the vehicle is travelling. However, the calculations are extremely complex and computationally demanding. Additionally, the calibration of a system using an influence surface requires multiple runs of the vehicle at different transverse locations and takes significantly longer than the calibration using an influence line. A new strips method was proposed by Žnidarič [18] as an enhancement to the original Moses algorithm. In this method, sensor strips take into account the transverse position of vehicles on the bridge but keep the calculation procedure relatively simple. The simple alteration to the original Moses method involves separating the results from the sensors into groups rather than into one value. The groups belong to individual lanes and this extra information was used to increase the accuracy. When a vehicle passed over the bridge the group of sensors under the lane it travelled in showed a higher response than the other sensor groups. Hence, allowing the identification of the transverse position of the load. The strips method was tested on bridges in Slovenia and Brazil and a sample of the results are shown in table 2. The proposed solution to the multiple presence issue is computationally efficient with easy installation with site calibration. These results show that using the strips method efficiently increases the accuracy of a B-WIM system.

Table 2 Results from WIM system using strips method [18]

Static GVW	WIM ERROR	
t	No Strips	Strips
22.76	-10.0%	-6.8%
20.76	-2.6%	-2.1%
44.91	-2.4%	-1.8%
44.26	-3.9%	-2.3%
52.06	-2.5%	-2.2%

5 Current Applications of B-WIM Data

5.1 Development of Load assessment methods

Design codes are developed for the design and assessment of bridge structures and allow safety factors on load models and materials but generally do not consider future increase in traffic loading. If all assessments are carried out in accordance with the design standards, this can lead to unnecessary repairs and costly replacements. Real traffic loads and frequency data can enable a value of the real safety of a bridge structure and prevent unnecessary repairs whilst proving real capacity.

University College Dublin (UCD) has collaborated with University of Alabama, Birmingham (UAB) to assess the current method of load rating bridges [29]. Data from B-WIM systems was used to develop live load factors to be used in the assessment of state owned bridges in

Alabama. The results show a significant change from the recommended rating method using ‘The American Association of State Highway and Transportation Official’s Load Resistance Factor Rating Manual’. The findings indicate the current method of load assessment for bridge evaluation is overly conservative. In Europe similar observations have been made on the problems of using the current design standards (BS EN 1991-2, 2003)as a method of assessing traffic loads on existing bridges [30]. This research concentrated on short to medium span bridges as this represents ~95% of the bridge stock in the world and used three known prediction methods to calculate extreme traffic loading from the data collected from two WIM sites.

A normal distribution of strain was fitted to the upper tail strain data and the block maxima strains. The peaks-over-threshold method was used to obtain maximum likelihood estimates for GVW. The block maxima method draws the largest values from blocks and the blocks are defined by measurement periods, that is, days or months. The peaks-over-threshold method extracts data from a continuous record, a threshold level is set and the peak values exceeding this are selected. These methods were used to extrapolate higher traffic loads, in this case GVW above 3.5t. The delta method and the profile likelihood method test the confidence in the extrapolations of GVW by limiting the variance. The data was collected from the A9 motorway near Montpellier, France and on the A31 motorway near Loisy, France. The data was collected over two different period lengths, 5 months of data was collected from the A9 site compared with only 2 months data from the A31 site near Loisy. The three methods were applied to extrapolate GVW 1000-year return for both WIM sites. The results indicate the larger sample size of data collected from the A9 site near Montpellier and using only weekday data provides more accurate results. The overall results demonstrate that the peaks-over-threshold method was the most suitable method to assess extreme traffic loads and the profile likelihood technique was more suitable than the delta method.

6 Next Generation B-WIM

Development of a next generation B-WIM system is on-going as part of collaboration between Queens University Belfast (QUB), University College Dublin and University of Alabama, Birmingham. The new system uses FBG sensors to develop an arrangement of NOR B-WIM sensors. The aim of this collaboration was to use advanced optical sensors below the deck that is, a NOR system to extend the safe working lives of bridges. Hence enhancing our understanding of deterioration in bridge structures and increased loadings, particularly incidences of overload which generally occurs in the night when no law enforcement agencies operate. Bridge reliability and safety assessments can be achieved by calculating the probability of the traffic loading exceeding the bridge's capacity to resist load by means of such sensors. Hence, the sensors can be used to determine the safety of the bridge and to detect any changes in bridge behaviour through longer term monitoring and enable an assessment of the causes of stress change. A new B-WIM sensor system, with sub micro strain accuracy, was developed by undergoing a series of laboratory testing which provided a performance comparison between fibre optic and electric resistance strain systems [31]. Although FBG systems may have higher initial cost compared to ERS, they are less demanding on power consumption. This is particularly advantageous in remote bridge sites and for long-term monitoring. FBG sensor systems can be designed using connectors to allow easy installation on site and therefore provide minimum disruption to the road network. This system was developed by the author and uses an innovative method of strain magnification to provide sub-microstrain accuracy [31]. In order to test the suitability of this sensor system for real B-WIM applications, a bridge structure on the main trunk road network connecting the first cities of Northern Ireland and Ireland was chosen. The bridge selected has a span of 19m and an angle of skew of 22.7° and is typical of the vast majority of medium span bridge in Europe, a beam and slab construction with the cast in-situ slab is supported by 27 pre-stressed concrete Y4 beams. As outlined in section **Error! Reference source not found.**, it has been reported that skew bridges with stiff pre-stressed beams may not be best suited to B-WIM as the overall stiffness of the structure reduces the measurable response to traffic loading. However, a full dynamic 3D FEA showed sufficient change of stresses under realistic traffic loads. The FEA was also used to establish the optimum location for the optical sensors prior to site installation.

In order to test the accuracy of the new B-WIM system a commercial pavement WIM (P-WIM) system was installed at the approach to the bridge structure. Traffic analysis on the data collected from the P-WIM indicated that the majority of HGV's travel in lane one, hence the optical sensor network was concentrated on the beams and slab most influenced by traffic in lane 1. The B-WIM algorithms require a measured change in longitudinal strain and, in order to measure this strain, the B-WIM sensors were attached to the soffit of 6 of the longitudinal beams. To complete the system a full set of fibre optic axle detecting sensors was also installed; this included 8 FBG sensors, 4 on the south quarter span and 4 on the north quarter span. The sensors were attached to the soffit of the slab under lane 1, they were orientated to measure change in transverse strain in the central region of the slab spanning between the beams.

The results from the FEA indicated that due to the stiffness of the structure low levels of strain were predicted for heavy traffic loading and hence a method of strain amplification would benefit the system [31]. To further magnify the strain data three sensors were aligned at the same location on the soffit of one beam, the output signal was summed thus enabling more accurate weight calculations. Initial testing of the system has provided very promising results.

The data shown in Table 3 was collected on site using the fibre optic based B-WIM system and subsequently processed using B-WIM software based upon the modified Moses algorithm. The software has been developed by the Slovenian National Building and Civil Engineering Institute (ZAG) and now forms part of the commercial B-WIM system SiWIM.

The adapted Moses algorithm in the SiWIM software was used to calculate the axle and GVW using strain signals obtained from the amplified fibre optic B-WIM (B) sensors system developed at Queens University Belfast. The calculated GVW are compared with the static weights obtained from a nearby static weigh station (S), and with the measured weights from the P-WIM (P) system for the same vehicle.

Table 3 Sample of site data

Vehicle no.	TYPE	GVW KG			Axle 1- KG			Axle 2- KG		
		S	B	P	S	B	P	S	B	P
1	6 Axle HGV	34680	33870	30810	5500	5450	4880	4550	5430	4240
2	5 Axle HGV	27890	27150	24730	6290	5800	5310	7850	8090	6550
3	3 Axle HGV	12650	12040	10160	5140	5270	3970	4600	3390	3890

Vehicle no	Axle 3- KG			Axle 4- KG			Axle 5- KG			Axle 6- KG		
	S	B	P	S	B	P	S	B	P	S	B	P
1	6980	5430	5970	5900	5860	5230	5930	5860	5540	5820	5860	4950
2	4460	4420	4160	4640	4420	4460	4650	4420	4250			
3	2910	3390	2300									

The results show that the error on the GVW from the B-WIM system ranges from 2% to 5% compared to the pavement WIM system which had errors between 11% and 20%. The high percentage of error in the P-WIM system was caused by a calibration drift in the TNL curves which needs to be continually maintained. This maintenance issue was not communicated by the manufacturer at the time of installation which resulted in a loss of confidence in the system. The error on the individual axle weights for the B-WIM system ranges from 1% to 26% with the highest error occurring in the distribution of weight between the rear pair of axles on the 3-axle vehicle. With improved post processing of the data the system has potential to provide results with the accuracy range for direct enforcement of overloaded vehicles. Although preliminary results show good potential for the system further analysis of a larger range of the data is required to determine the true accuracy classification. It is clear from the results presented above that the fibre optic system provides much more accurate results, this can be attributed to the fact that when compared to the conventional electronic strain gauges the results from the FOS have provided clearer signals which require less filtering and less post processing procedures

7 Contactless B-WIM

Contactless Bridge Weigh in Motion (cBWIM) uses bridges to weigh vehicles without the need for any sensors to be attached to the structure. The concept is to use two cameras which have been time synchronised, the first to measure sub-millimetre deflections on the underside of the bridge and a second monitors passing traffic on the bridge surface. This provides a great advantage in situations where access to the underside of the bridge is restricted, thus making it very difficult to attach sensors. This method increases safety, is far quicker to set-up and can provide instant information on live traffic loading. However, a truck of known weight is required to calibrate the system at each set up, making it more suitable for short term monitoring. [32] The system was trialled on the same bridge used for the testing of the next generation B-WIM system as detailed in section 8. Measurements were taken over the course of a day, to calibrate the system eight vehicles were selected from the live traffic and statically weighed at a nearby weigh station. The video images from the above deck camera were used for axle detection, a notional vertical line was chosen in the frame and the number of frames between each axle passing the line was used to calculate the spacing between the axles. The accuracy of the cBWIM system for the selected vehicles is shown in table 4, the results indicate the accuracy achieved was relatively low in comparison with those presented in section 8.

Table 4 Accuracy of cBWIM system

Vehicle No.	No. of Axles	Gross weight Error	Single Weight Error	Group Axles Weight Error
1	5	-11.5%	42%	111%
2	5	-4.1%	7%	25%
3	5	5.7%	35%	119%
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 GVW accuracy is better than individual or group axle weights but the overall accuracy has the potential to be greatly improved by adding more cameras and hence increasing the number of measurement points.

8 Conclusions

This paper has reviewed past and recent developments in B-WIM and highlights the advances in B-WIM technology in terms of sensor system development, data acquisition, filtering techniques, collection of critical information from data and advancing theoretical methodologies. A B-WIM system with accuracy levels which enable direct enforcement has not been developed to date but since its introduction in the 1970’s the use of alternative sensing technology such as FOS had not been explored until now. Extensive work was previously carried out on the development of post processing methods and algorithms but there has been a significant shortfall improving the actual system installed on site, the challenge is to apply the theory in the field and assess the real results. To explore the full potential of B-WIM the system needs utilise new and more innovative measurement methods such as the optical fibre approach described in section 8. The development of a portable B-WIM system which is also suitable for long-term monitoring would be extremely beneficial to the road network and can provide an early warning system alongside existing bridge management programs. A successfully developed FOS B-WIM system could fulfil this purpose and provide a clearer understanding of the current state or our bridge stock and the loading it is subjected to on a daily basis. Previous B-WIM installations highlighted limitations, such as insufficient axle detection methods and multiple presence issues. This has been discussed and potential solutions presented. Previously, due to the limited number of research based field installations, recommendations on suitable bridge sites had advised against the implementation of B-WIM systems on skewed or prestressed structures limiting the applicability of the system. The next generation B-WIM system has addressed this concern and hence expanded the range of bridge sites suitable for B-WIM installations to skew and slab and beam. The incorporation of emerging sensing technology can improve the accuracy and reliability of B-WIM. Many of the strategies discussed are just beyond inception stage and have potential to be developed into highly accurate tools for traffic loading analysis and structural health monitoring of our future infrastructure.

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