ON THE USE OF BRIDGE WEIGH-IN-MOTION FOR OVERWEIGHT TRUCK ENFORCEMENT

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ABSTRACT

Bridge weigh-in-motion (B-WIM) is a method by which the axle weights of a vehicle travelling at full highway speed can be determined using a bridge instrumented with sensors. Since the sensors are attached to the underside of a bridge, the instrumentation can be installed without disruption to traffic. This paper looks at the history of B-WIM, beginning with early work on weigh-in-motion technologies in the 1960's leading to its invention by Fred Moses and George Goble in the United States in the mid 1970's. Particular attention is devoted to Moses' original algorithm, which has been used by many systems since 1979 and is still utilized today by commercial developers of B-WIM systems. Research initiatives in Australia and Europe over the past 15 years have focused on improving B-WIM accuracy either by improving Moses' original algorithm or by developing new methods. The moving force identification (MFI) method models the dynamic fluctuation of axle forces on the bridge and holds particular promise. B-WIM accuracy depends on bridge site conditions as well as the particular data processing algorithm. The accuracy classifications of several B-WIM installations reported in the literature are summarized in this paper. Current accuracy levels are sufficient for selecting vehicles to be weighed using static scales, but insufficient for direct enforcement.

Keywords:
Trucks, Bridges, Weighing Devices, Overweight Enforcement, Weigh-in-Motion, State-of-the-Art

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INTRODUCTION

The weighing of vehicles for enforcement first began in the United Kingdom in 1741 when the Turnpike Act was introduced. This act decreed that tolls were to be paid for using the roads according to the weight of the vehicle. The money raised from these tolls was to be used for the maintenance of the roads, similar to how revenue raised from heavy or overweight vehicles is used today (Sanders 2010).

Currently, a variety of methods are used to weigh highway vehicles. These methods can be classified as either:

- static - the vehicle is weighed while stationary on the scale,
- low-speed weigh-in-motion (WIM) - the vehicle is weighed while it moves across the scale at low speed, typically 5 to 15 km/hr, or
- high-speed WIM - the vehicle is weighed at full highway speeds

Static Weighing and Low-speed WIM

Static scales are the most cumbersome but the most accurate. Three types of static scale are generally used:

- Fixed Systems are permanently mounted to the pavement, typically in a reinforced concrete frame or platform. All weighbridges and some wheel and axle scales work like this.
- Semi-Portable Systems use permanent grooves and road installations but with portable scales which are installed only while weighing operations are being carried out.
- Portable Systems use either wheel or axle scales which are placed on the pavement surface. These can be complemented with leveling plates or ramps to ensure that the wheels being weighed are on the same plane.

Static scales are the most time consuming method of weighing vehicles, making these methods costly for both highway agencies and vehicle operators. The time required to weigh a vehicle can be reduced significantly with low-speed WIM devices. Low-speed WIM devices are typically wheel or axle scales equipped with load cells, and are usually installed into reinforced concrete or asphalt platforms which are at least 30-40 m in length. The vehicle may be guided by curbs to minimize variation in the transverse position of the wheels. The data processing system analyzes the signal from the load cells and takes the vehicle speed into account in order to accurately calculate wheel or axle loads. The operating speed is typically between 5 and 15km/h.

Static scales and low-speed WIM devices are very accurate and are used for enforcement in many US states and in several European countries such as Germany and France (Jacob and La Beaumelle 2010). Both types of weighing devices require vehicles to exit the highway, however, and often wait in a queue to be weighed one at a time. For highways with heavy truck traffic, this can result in delays for the vehicle operator of between 10 and 30 minutes. Some permanent weigh stations screen the vehicles with less-accurate high-speed WIM devices installed on the exit ramp. Vehicles with WIM-measured axle weights well below the legal limits are diverted to a bypass lane to re-enter the highway.

Efforts have been made to move away from static and low-speed weighing devices as they are expensive to staff and can induce lengthy wait-times for the drivers.   Statistical data from static weighing campaigns is sometimes biased as drivers of overloaded vehicles make efforts to avoid being weighed. Further, high traffic volumes on many highways have led to static weighing becoming ineffective, and as such can be a limited deterrent. Excessive queues often form at static weighing stations, causing access to the weigh stations to be temporarily shut, and thus allowing overweight vehicles to pass by without being weighed. In Europe, the mean time between two checks of a truck that operated every day was almost 30 years (Jacob and La Beaumelle 2010).

High-speed WIM

High speed WIM systems take measurements directly in the traffic lanes and calculate axle weights at full highway speed.   Most high-speed WIM installations are unmanned and can therefore collect data 24 hours a day. These devices are either installed in the pavement or on the underside of a highway bridge. Several types of pavement-based high-speed WIM device exist, including bending plates, strip sensors, and multiple strip sensors. Alternatively, high-speed WIM can be accomplished using bridge weigh-in-motion (B-WIM) devices.

Bending plate and load cells use metal plates which have been instrumented with sensors on their underside. Load cell systems are either hydraulic or have strain gauges. Typically two 2' x 6' plates are placed adjacent to each other in a 12' lane. The measured strains are analyzed and the axle loads are calculated (Bushman & Pratt, 1998). The main disadvantage of these plates is that their installation requires the closure of traffic lanes and construction of a substantial support structure.

Strip sensors were introduced in the early 1980's. A typical strip sensor consists of a narrow bar, a strip or a wire with a cross-section of a few mm^2 or cm^2. These devices extend the full width of a traffic lane or half the width of a traffic lane. Unlike plates, where the full tire imprint is on the sensor, these sensors are very narrow and do not directly measure the wheel or axle load. The sensors measure pressure, strain or force and use an algorithm to calculate the loads with respect to vehicle speed and estimated tire characteristics. Various types of strip sensor are currently in use including piezo-ceramic, piezo-quartz, piezo-polymer and optic fibers. Strip sensors are cheaper than plates and require less civil engineering work for installation. However, their accuracy is highly dependent on pavement characteristics (especially its roughness and modulus), and they cannot be calibrated using standard masses (Jacob and La Beaumelle 2010).

Multiple strip sensors consist of a series of strip sensors installed over a short length of roadway (10 to 50m). The multiple measurements can be averaged or combined in some way (Dolcemascolo et al. 2002) to minimize the effect of dynamic wheel forces, providing a more accurate estimate of the static axle forces. These devices are best calibrated using the true wheel dynamic forces rather than static wheel forces. The accuracy of these systems depends upon the number and quality of sensors, the data-processing algorithm and the pavement condition (Jacob and La Beaumelle 2010).

Bridge weigh-in-motion (B-WIM) systems comprise strain measuring instruments mounted onto the underside of a bridge. As such it is unnecessary to interrupt traffic during installation which is an important advantage of B-WIM. Vehicles are in contact with the bridge for a much longer time than for the other types of high-speed WIM, making it (theoretically) possible to minimize the effects of dynamic loads. An inherent disadvantage of B-WIM devices is that the bridge

structure is an integral part of the weight measurement system. The instrumented components of a bridge need to respond consistently and predictably over a range of vehicle weights, speeds and transverse positions (middle of the lane vs. edge of the lane).

EARLY B-WIM DEVELOPMENT

Bridge weigh in motion was pioneered by Fred Moses and George Goble in the United States in the early 1970's. It was successfully applied to bridges in Australia by Rob Peters in the mid 1980s who went on to develop a simpler version for culverts.

Early Interests and Accomplishments

Interest in weighing trucks electronically was first reported in a 1961 Michigan State Highway Department report which summarized over 20 years of work related to the issue (Epsco, Inc and Michigan State Highway Department, 1961). Based on this work, a platform load cell was installed on a special lane adjacent to a weigh station.

Lee and Nasser (1968) reported on the design, construction and testing of an early WIM system in Texas. It was capable of measuring and recording in-motion measurements of vehicle speed, vehicle length, time of day, number of axles, axle spacing and wheel weights without impeding normal traffic flow. The Texas system was similar to a system developed and tested in the United Kingdom (Trott and Grainger 1968). California developed a related system capable of classifying vehicles according to wheel base and number of axles (Nordlin et al. 1969). Carr and Rizenbergs (1971) documented early work in Kentucky on developing WIM systems. Their report focused on the need for portability and flexibility in such systems. Further successful development of portable WIM systems was conducted in Texas in 1974. Tests were performed under ideal conditions using five project trucks of different classifications. The study explicitly addressed vehicle speed and pavement profile characteristics (Machemehl et al. 1975)

Goble, Moses and Pavia in the Beginning

George Goble, Fred Moses and Anthony Pavia performed early investigations into technologies and systems that would become B-WIM at Case Western Reserve University under the sponsorship of the Ohio Department of Transportation and the Federal Highway Administration (Goble et al. 1974). The goal of the original research was to improve the measurement and processing of bridge strain histories so that sufficient data could be collected for statistical analyses of bridge fatigue life. Ten girder slab highway bridges in the state of Ohio were instrumented with strain gages and data was recorded under normal traffic conditions for periods of 12-24 hours each. The project was the first to systematically record truck headways and correlate the closely spaced trucks with stress range. Some of the bridge measurements were made in conjunction with a weighing station. Comparison of the bridge and the weigh station data showed that it was feasible to use the bridge as a weigh scale (Goble et al. 1976).

Fred Moses in the US (1979)

Fred Moses (Moses 1979) published a frequently cited article laying out the methodology for using measured bridge strain histories to estimate truck axle weights. He pointed to the longer contact time between the vehicle and the bridge as a potential advantage over pavement-based weigh-in-motion devices. Since the vehicle is in contact with the bridge for a much longer time, more measurements are recorded and dynamic effects can be minimized by a statistical

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smoothing algorithm. The longer contact time is a disadvantage, however, when trying to separate the effects of closely-spaced axles.

The system developed by Moses consisted of:

- A Button Box – An operator was located approximately 100ft before the bridge with a button box. When a truck was seen, the operator pressed the button which alerted the system of a truck arrival.

- Tape Switches – Two tape switches were fastened to the pavement in the same lane a set distance apart for the purpose of determining vehicle velocity, axle spacing and axle position. A third tape switch was located immediately before the bridge and this was used to tell the system to begin taking strain readings for a set amount of time. This time was based on the lowest expected velocity of a truck crossing the bridge. A tape switch consisted of two metallic strips which were held out of contact. As a tire passed over the switch, the metallic strips were forced into contact and a signal was generated at the instant the axle crossed the switch.

- Strain Transducers – Strain gauges were placed on the bottom flange of each girder along a line parallel to the direction of the bridge. The mid-span was suggested as being the most suitable location. The strain record for each gauge was recorded separately on magnetic tape. The signals from all girders were summed in the processing program after collection.

- An Instrument Van – The signals from the traffic detectors and strain transducers were sent to a van which was located beneath the bridge to avoid detection from passing vehicles. The traffic signals, which were already in digital form, went directly into the computer while the strain signals were sent to the signal conditioners. The output signals from the signal conditioners were then sent to the analog-to-digital converter of a minicomputer system for recording on magnetic tape.

Weigh-in-motion is an inverse type problem: the structural response is recorded and the load causing that response must be calculated. An influence line of the bridge must either be calculated by structural analysis or by using a calibration truck of known static axle weights.

$$E = \sum_{k=1}^{T} \left[M(t_k) - M^*(t_k) \right]^2 \qquad (1)$$

where:

E = the sum of the squared errors between the predicted and the measured bridge response

k = the time increment of the measured bridge response (strains)

T = number of time increments

$M(t_k)$ = the predicted bridge response (moment or strain) for the kth time increment (summed for all instrumented girders)

$M^*(t_k)$ = the measured bridge response for the kth time increment (summed for all instrumented girders)

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The predicted bridge response is calculated using an influence diagram. The influence diagram represents the bridge response at a particular location (say bending moment at midspan) due to a unit load at each longitudinal location along the bridge.

At a given point in time, the predicted bridge response is calculated as the sum of the axle weight times the influence diagram value for each axle.

$$M(t_k) = \sum_{i=1}^{N} A_i I_i(t_k) \qquad (2)$$

where:

A_i is the axle weight of the ith axle

$I_i(t_k)$ is the influence diagram value for the ith axle at the kth time increment and

N is the number of axles.

The influence line may be calculated using the recorded strains from the calibration truck, for which the axle weights and spacings are known. Substituting Equation 1 into Equation 2:

$$E = \sum_{k=1}^{T} \left[\sum_{i=1}^{N} A_i I_i(t_k) - M^*(t_k) \right]^2 \qquad (3)$$

The axle weights (A_i) of unknown trucks are then calculated by finding the A_i which minimizes the sum of the squared errors, E. This is achieved by taking partial derivatives of E with respect to each axle weight. Setting the partial derivatives to zero gives a set of simultaneous equations in A_i. Moses (1979) showed that the least-squares minimization process fits a static predicted response to a measured dynamic response.

Moses used a three span, continuous beam and slab bridge for testing the system. Only the first span of the bridge was instrumented. The calibration tractor-trailer vehicle passed over the bridge 13 times: the coefficient of variation of the measured gross weights was 5%. The coefficient of variation for the rear tandem weights was found to be 10.1%. Weighing of random vehicles was also conducted in conjunction with a static weighing station located 40 miles downstream from the bridge. As a result of this long distance only 20 vehicles were positively identified as having crossed the bridge and weighed at the station. Moses suggested that single short spans (under 60ft) were most suitable to predict individual axle weights while a larger span (over 80ft) was more appropriate for determining gross weights.

Rob Peters in Australia (1984)

The next major development in B-WIM came in 1984 from Australia when R.J. Peters developed the AXWAY system (Peters 1984). Peters proposed to determine axle and gross weights of passing trucks using an instrumented bridge. Electrical resistance stain (ERS) gauges were bonded to the deck reinforcement of Maddington Bridge on the Beechboro Gosnells Highway in 1980 while it was being built. As predicted, the strain readings from the gauges were too small

to be consistently measured and so a mechanical strain amplifier (MSA) was developed. This MSA gave amplification of between four and ten times actual strain.

It is noted by Peters that the development of axle detectors was one of the most difficult problems in the implementation of AXWAY. The author stated that they must be reliable, waterproof and durable. Air hoses were found to give good speed measurements but were poor at counting axles, often overestimating the number of axles on a truck. Photo-electric cells, where a beam of light is directed across the road just above the surface, were found not to provide good results. A third system using burglar alarm mats was found to be 95% accurate which was satisfactory for the AXWAY system.

AXWAY was a manned system and it was therefore expensive to collect large volumes of data. Peters went on to develop a new unmanned system he called CULWAY (Peters 1986). His new 'low cost/low power single lane system for unattended operation' weighed an axle of a vehicle as it crossed over a culvert. Dynamic effects and vibration, a major source of error for bridge-based WIM systems, are virtually non-existent with culverts as the soil between the culvert and the pavement damps out the vibration. Another advantage of culvert-based WIM is that culverts do not have abutments and the associated vehicle dynamic forces caused by even small vertical misalignments between the approach roadway and the bridge deck.

Two tape switch axle detectors were placed on the road surface. The first was placed 9.8m before the center of the culvert span while the second was placed 0.2m past the center. The tape switches were used to determine the vehicle speed, the axle position and spacing and to tell the system to begin taking strain measurements. Mechanical strain amplifiers were attached to the roof of the culvert. The first trials took place in July 1984 and the plotted strains were both substantial and clear of the vibration problems found with bridges. The instrumented culvert had two cells, which meant the instrumented cell was placed in negative bending when the uninstrumented cell was loaded. This meant that this type of culvert would be unsuitable for CULWAY. The next two installations were unsuccessful as both had over 2m of fill which meant that the strain signals were very weak.

The first trials with test trucks took place on a culvert with a span of 2.4m. This trial achieved good results although some issues arose. The road surface on the approach to the culvert was uneven and settlement had taken place as it had been constructed after the road. The CULWAY system used peak strain as opposed to Moses' process of fitting to the full strain record, to calculate the axle weights. For the 2.4m span the measured peak strain value was caused by more than one axle of a tandem or tridem which makes it difficult for such an algorithm to determine their individual weights. From these trials the following criteria were set for the selection of suitable culverts:

- single span of less than 2.7 m
- good road surface
- no skew
- soil cover should be between 200mm and 1500mm.

Overlapping influence of axles occurred when the culvert's effective span was more than twice the axle spacing; this often occurred for tandem axles or triaxles. Without a correction these axles would be overweighed, especially the middle of a triaxle group. The CULWAY system was required to be calibrated using trucks of known weight. Although it was recommended that

random trucks from the traffic stream be statically weighed and used for calibration, the use of at least one articulated, tandem drive vehicle with a triaxle semi-trailer could also suffice. An accuracy of +/-10% was obtained on a sample of 1296 trucks (Peters 1986).

European B-WIM Developments

Outside of Australia, there was little interest or development of B-WIM until the late 1990's. The COST 323 program was an intergovernmental framework for European Co-operation in the field of Scientific and Technical Research. It was the first European co-operative action on weigh-in-motion of road vehicles and it resulted in a specification of WIM systems, two conferences and some large scale tests of B-WIM systems (Jacob et al. 2002). In addition, the WAVE (Weighing-in-motion of Axles and Vehicles for Europe) project in the late 1990s fostered extensive research into WIM in general (Jacob and OBrien 1996, Jacob 1999) and B-WIM in particular (OBrien and Žnidarič 2001).

The results of this work are summarized in the following three sub-sections. First, **axle detection** techniques are used for calculating vehicle velocity and axle position and spacing. Next, strain measurements from different transverse positions on the bridge can be used to form a **surface of influence lines**. Finally, various **dynamic models** of the axle loads on the bridge are used to improve B-WIM accuracy.

Axle Detection

Earlier B-WIM systems used either removable pneumatic hoses or tape switches or permanent low-grade piezo-electric sensors embedded in the pavement. Two detectors in each lane provide sufficient information for calculating vehicle velocity, axle spacing and axle position on the bridge (Žnidarič and Baumgärtner 1998; Obrien et al. 1999). Measured strains in longitudinal stiffeners separated longitudinally on a steel orthotropic bridge deck in France were used for axle detection (Dempsey et al. 1998b; Dempsey et al. 1999). Such an installation, termed "free of axle detectors" or "nothing on the road" (NOR), does not disrupt traffic during installation and is not visible to drivers crossing the bridge. NOR axle detection was also implemented on integral slab bridges (Žnidarič et al. 1999a).

Accurate measurement of vehicle velocity is essential for accurate determination of axle weights from measured strain histories. Several techniques have been used for improving the accuracy of velocity determination. Velocity can be included in the optimization process (Dempsey et al. 1998a; Žnidarič et al. 1999a), a strategy which improves accuracy but which requires a good initial estimate. The identification of discontinuities in strain histories as axles pass overhead can be improved using wavelet domain analysis (Chatterjee et al. 2006). More accurate measures of velocity result from this improved information on axle position at given points in time. Velocity can also be calculated by correlating strain histories from two longitudinal positions on the bridge (Kalin et al. 2006), an approach similar to that proposed by Dempsey et al (1998a).

Finding the influence lines

Early B-WIM systems used theoretical influence lines but it quickly became apparent that this is insufficient for an accurate system. Bridges are generally stiffer than suggested by Finite Element models, probably due to the contributions of non-structural elements such as the pavement and parapets. Also, the rotational restraint at girder ends due to debris or deteriorated

bearings is difficult to predict. Žnidarič and Baumgärtner (1998) adjust an initial estimate of influence line interactively until a good match is achieved between the measured and theoretical responses to a pre-weighed calibration truck. McNulty and OBrien (2003) also update an initial estimate to match the response to a calibration truck but on a point by point basis. OBrien et al. (2006) develop a matrix approach, which, in the spirit of the original Moses algorithm, finds the optimum solution for all points making up the influence line.

The transverse position of a vehicle in the lane can affect the accuracy of the calculated axle weights (Dempsey et al. 1999). This was especially noticeable on a steel orthotropic deck bridge in which the main girder had a stiffening effect on nearby longitudinal stiffeners. One solution is to calculate separate influence lines for each instrumented stiffener, thus forming a two-dimensional surface of influence lines. Use of the two-dimensional surface improved the accuracy of predicted axle weights on an integral slab bridge in Sweden (Quilligan et al. 2002). The system was difficult to calibrate in the field, as the transverse position of the calibration truck as it passes over the bridge was not easily obtained. The effect of variations in the transverse position of vehicles within the lane on the accuracy of predicted axle weights is minimal for bridges with relatively high transverse stiffness (Žnidarič and Baumgärtner 1998).

Japanese B-WIM Efforts

In the 1980's in Japan, Miki (Miki et al. 1987; Kobayashi et al. 2004) proposed NOR B-WIM for steel plate girder bridges based on Moses's concept. Instrumented vertical stiffeners on the web plate were used as axle detectors, with mixed success. Matui and El-Hakim (1989) found that crack openings in the reinforced concrete slab were sufficiently sensitive to detect axle load, although this approach presupposes the presence of cracks. Ojio et al. (1998) carried out a feasibility study of B-WIM in orthotropic steel decks using strain in the longitudinal stiffeners for axle detection. Six sensors at two sections were found to be sufficient to detect axles for the full range of transverse positions, tire widths and types.

Dynamic Models and Moving Force Identification

O'Connor & Chan (1988a, 1988b) develop a dynamic B-WIM algorithm with the purpose of identifying high-impact vehicles on short span bridges. Ghosn and Xu (1988) present a modified B-WIM algorithm that allows the calculation of the dynamic amplitude of the bridge vibration in addition to the static axle weights of a truck as it traverses a bridge. The dynamic response of a bridge to moving constant axle force was calculated using modal superposition by Dempsey et al. (1998a). The damping ratio was estimated at 2% and the natural frequency was calculated based on the bridge geometry for a theoretical study, and measured for an experimental study. Predicted bridge strains at a single longitudinal position were calculated from the predicted displacements for the experimental study. The dynamic axle load identification algorithm had less error than the static model (Moses) load identification algorithm for both studies.

The forces exerted through a vehicle's wheels to a bridge are not constant with time due to rocking and bouncing of the truck (OBrien and Kealy 1998). They reported links between the number of axles and the number of required sensor locations with more sensors being required for vehicles with more axles. This approach was found to be more effective for a continuous two-span bridge than for a simply supported bridge.

In the late 1990s and early 2000s, several researchers, investigated the differences between theoretical B-WIM algorithms and bridge measurements, both theoretically using complex

vehicle-bridge dynamic interaction models and experimentally using data from four bridge sites (González 2010; González and OBrien 1998; Law et al. 1997; Law et al. 1999; Yu and Chan 2003; Zhu and Law 2001; Law et al. 2004; Law and Fang 2001). The influence of dynamics and multiple sensors on the accuracy of B-WIM systems is addressed. González (2010) also describes the development of a B-WIM system in Ireland, including all aspects of installation, calibration, data collection and processing into useful traffic information. Rowley et al. (2008) find that Moses's equations are ill conditioned when axles are closely spaced relative to bridge span. In simulations and field trials, they demonstrate that considerable improvements in accuracy can be achieved using Tikhonov Regularization to improve the conditioning of the equations. Dowling et al. (2010) have gone on to propose calibration solutions for an MFI-based approach to B-WIM. In a separate development, OBrien et al. (2010) propose a 'filtered measured' approach to B-WIM. This applies Moses' algorithm to the strain signal after dynamic effects have been filtered. This approach is unique in that the same filter is applied to the signal corresponding to the calibration truck as to the other signals.

The time history of axle forces crossing a bridge can be calculated from measured bridge strain histories using a sophisticated and promising technique: regularized moving force identification (González et al. 2008). The static axle forces (or weights) can be calculated from the axle force time histories. Briefly, the method involves formulating the equations of motion of the bridge with the help of a finite element model. The model can be adjusted using the measured frequencies and damping ratios from bridge strain measurements (Rowley et al. 2009). The number of equations required is reduced using modal superposition, ill-conditioned solutions are improved using Tikhonov regularization, and the optimal predicted axle weights to minimize the differences between the measured and the predicted strains are calculated using dynamic programming. Application of the moving force identification (MFI) technique on synthetic data has demonstrated that the accuracy of MFI is less affected by signal noise and vehicle dynamics than the traditional Moses B-WIM method. The MFI technique also predicts axle weights from measured strain data with consistent accuracy.

B-WIM ACCURACY

After durability, the ultimate utility of a WIM installation is governed by its accuracy. One of the principal outcomes of the COST 323 program was the development of a procedure to consistently assess the accuracy and reliability of a WIM system based on a vehicle-by-vehicle comparison of WIM-predicted weights and static weights. Many factors affect the accuracy of a B-WIM installation, and unfortunately current knowledge is not at the point where the suitability of a candidate bridge for B-WIM can be reliably predicted. The importance of several factors regarding B-WIM installation is highlighted by a review of numerous B-WIM installations and reported accuracies.

COST 323 WIM Accuracy Classification

In order to clarify the real level of accuracy and performance of various WIM systems throughout Europe, a common European WIM Specification was developed (Jacob 2000, Jacob et al. 2000). This task was one of the main priorities of the COST 323 action on WIM of road vehicles. The first two years of its development involved an analysis of existing and emerging specifications and other technical documents. After discussions with European manufacturers and users' representatives, a revised draft was published in June 1997. The appendix of the specification provides a set of rules for categorizing the accuracy of a WIM system based on a

statistical comparison between the WIM-determined weights and the corresponding static-scale-determined axle weights. A good explanation of factors affecting WIM site accuracy, and an example accuracy classification using real WIM data are provided by Jacob et al. (2000). A more technical explanation of the background statistical concepts is given by Jacob (2000).

Six accuracy classes are defined (see Table 1): A(5), B+(7), B(10), C(15), D+(20), D(25) and E (COST 323 1999). The last class can be split further: E(35), E(40) etc. The numbers in brackets represent the allowable errors or tolerances (in %) in the WIM-measured gross weights. There are specified confidence interval widths (δ) for the error in a single axle weight, the weight of an axle group, weight of an axle within a group, and the vehicle gross weight. If the same data is used for calibration and for calculation of the accuracy class, then the tolerances should be multiplied by 0.8.

Table 1. Confidence interval width (δ in %) for each accuracy class (after Jacob et al, 2000)

Type of Measurement	Domain of use	Accuracy Classes: Confidence interval width δ(%)					
1.		A(5)	B+(7)	B(10)	C(15)	D(25)	E
2. Gross Weight	Gross weight >3.5 t	5	7	10	15	25	>25
Axle Load:	Axle load > 1 t						
3. Group of axles		7	10	13	18	28	>28
4. Single axle		8	11	15	20	30	>30
5. Axle of a group		10	15	20	25	35	>35

Classes A(5) and B+(7), are recommended for legal purposes such as overload enforcement; classes B(10) and C(15) are recommended for overload pre-selection and detailed traffic analysis, and classes D+(20) and D(25) are mainly used for economic and technical studies and general traffic evaluation.

For a given accuracy class, there must be an acceptable level of confidence that WIM errors, relative to the reference (static) values, are within the interval width, δ. Minimum acceptable levels of confidence are defined which depend on the number of vehicles in the data set, on the variability of the test (variability of the truck speed, lateral position and axle configuration), and on the variability of the environmental conditions (principally temperature). Four sets of test conditions are defined in Table 2, shown in order of increasing variability. Three sets of environmental conditions are shown in Table 3, also shown in order of increasing variability.

The minimum acceptable levels of confidence that the WIM weights are within a specified interval (from Table 1) are shown in Table 4 for Environmental Condition I (Environmental Repeatability), Note that for a given number of trucks, the minimum acceptable levels of confidence decrease as the variability of the test conditions increase. Tables 5 and 6 show the minimum acceptable levels of confidence for the other two environmental conditions.

Table 2. Test conditions (after Jacob et al, 2000)

Test Conditions	Description
r1. Full Repeatabilty	One vehicle passes several times at the same speed, load and lateral position.
r2. Extended Repeatability	One vehicle passes several times at different speeds and with small variations in lateral position (in accordance with typical traffic).
R1. Limited Reproducibility	A small set of vehicles (usually 2 to 10), representative in weight and silhouette of typical traffic, is used. Each vehicle passes several times, at different combinations of speed and load and with small variations of lateral position.
R2. Full Reproducibility	A large sample of vehicles (some tens to a few hundred), taken from the traffic flow and representative of it, is used for the calibration.

Table 3. Environmental conditions (after Jacob et al, 2000)

Environmental Conditions	Description
I. Environmental Repeatability	The test time period is limited to a couple of hours within a day or spread over a few consecutive days, such that the temperature, climatic and environmental conditions do no vary significantly during the measurements.
II. Limited Environmental Reproducibility	The test time period extends at least over a full week or several days spread over a year, such that the temperature, climatic and environmental conditions vary during the measurements but no seasonal effect has to be considered.
III. Full Environmental Reproducibility	The test time period extends over a whole year or more, or at least over several days spread over a year, such that the temperature, climatic and environmental conditions vary during the measurements and all the site seasonal conditions are encountered.

Table 4. Minimum acceptable levels of confidence under *Environmental Repeatability (I)* (after Jacob et al, 2000)

Calibration Conditions	Number of Trucks:	10	20	30	60	120	∞
r1. Full Repeatabilty		95	97.2	97.9	98.4	98.7	99.2
r2. Extended Repeatability		90	94.1	95.3	96.4	97.1	98.2
R1. Limited Reproducibility		85	90.8	92.5	94.2	95.2	97.0
R2. Full Reproducibility		80	87.4	89.6	91.8	93.1	95.4

Table 5. Minimum acceptable levels of confidence under *Limited Environmental Reproducibility (II)* (after Jacob et al, 2000)

Calibration Conditions	Number of Calibration Trucks:	10	20	30	60	120	∞
r1. Full Repeatabilty		93.3	96.2	97.0	97.8	98.2	98.9
r2. Extended Repeatability		87.5	92.5	93.9	95.3	96.1	97.5
R1. Limited Reproducibility		81.9	88.7	90.7	92.7	93.9	96.0
R2. Full Reproducibility		76.6	84.9	87.4	90.0	91.5	94.3

Table 6. Minimum acceptable levels of confidence under *Full Environmental Reproducibility (III)* (after Jacob et al, 2000)

Calibration Conditions	Number of Calibration Trucks:	10	20	30	60	120	∞
r1. Full Repeatabilty		91.4	95.0	96.0	97.0	97.6	98.5
r2. Extended Repeatability		84.7	90.7	92.4	94.1	95.1	96.8
R1. Limited Reproducibility		78.6	86.4	88.7	91.1	92.5	95.0
R2. Full Reproducibility		73.0	82.3	85.1	88.1	89.8	93.1

Test condition R1 (Limited Reproducibility) is recommended for WIM site calibration. Since calibration is typically completed in a single day, environmental condition I (Environmental Repeatability) usually applies. Environmental condition II (Limited Environmental Reproducibility) typically applies for in-service weighing of trucks from the traffic stream. Collecting WIM data for a year or more without recalibration is not recommended.

In 2007, the Forum of European Highway Research Laboratories (FEHRL), in a project known as the FEHRL institutes WIM initiative (FiWi) (http://www.fehrl.org/index.php?m=140, accessed June 2011), revised the COST 323 specification and submitted it to the European Normalization Committee as a draft pan-European standard in WIM.

Accuracy reported from B-WIM Field Tests

COST 323 accuracy classifications have been published for a multitude of B-WIM sites, mostly in Europe. Brief descriptions of the bridge, data analysis techniques, and reported accuracies for nine B-WIM sites are provided below; the data is summarized in Table 7.

A reinforced concrete box girder bridge in Slovenia (Site 1 in Table 7) was instrumented and tested with two early B-WIM systems: one from the US and one from Ireland (OBrien et al. 1999). Gross weight accuracy was D(20) and overall accuracy was E(50) for both systems. The authors attribute the poor accuracy to bridge and vehicle dynamics at the less-than-ideal site.

Table 7. Accuracy classifications from nine B-WIM sites

Site	Bridge Type	Length of Inst'd Span	Traffic	Location	Reference	Comment	Single Axle	Axle Group	Gross Wt.	Overall
							- - - - Accuracy Classification - - - -			
1.	RC Box Girder	11.8 m	2-lane, 2-way	Slovenia	OBrien 1999	American System	E(50)	E(50)	D+(20)	**E(50)**
	"	"	"	"	"	Irish System	E(50)	E(50)	D+(20)	**E(50)**
2.	Steel Orthotropic Deck	75 m	4-lane, 2-way	Autreville France	Dempsey 1999	1D Influence Line	D+(20)	D+(20)	D+(20)	**D+(20)**
	"	"	"	"	"	2D Surface of influence lines	C(15)	C(15)	C(15)	**C(15)**
3.	RC Integral	10 m	2-lane, 2-way	Slovenia	Znidaric 1999	Experimental influence line	D+(20)	B+(7)	C(15)	**D+(20)**
	"	"		"	"	Data processing enhancements	B(10)	B(10)	B(10)	**B(10)**
4.	RC Integral	9.6 m	2-lane, 2-way	Slovenia	Znidaric 1999	Skewed 7°	D+(20)	B+(7)	B(10)	**D+(20)**
5.	"	"	"	"	"	Skewed 26°	C(15)	B+(7)	B+(7)	**C(15)**
6.	RC Integral	8 m with a bump	2-lane, 2-way	Slovenia	Znidaric 1999	All trucks	D(25)	E(40)	B(10)	**E(40)**
	"	"	"	"	"	Only trucks heavier than 20 kn	C(15)	C(15)	B(10)	**C(15)**
7.	RC Integral	10 m	4-lane, 2-way	Sweden	Quilligan 2002	1D Influence	B(10)	B+(7)	B(10)	**B(10)**
	"	"	"	"	"	2D Influence	B+(7)	A(5)	B+(7)	**B+(7)**
	"	"	"	"	"	2D Infl. + Multi-Pres.	B(10)	A(5)	B(10)	**B(10)**
8.	RC Integral	15 m	2-lane, 2-way	Sweden	McNulty, 2003	Summer 1997	C(15)	B(10)	B(10)	**C(15)**
	"	"	"	"	"	Winter 1998	C(15)	D+(20)	C(15)	**D+(20)**
	"	"	"	"	"	Summer 1998	B(10)	B(10)	B(10)	**B(10)**
9.	RC Integral	8 m	2-lane, 1-way	France	Bouteldja 2008		B(10)	C(15)	B(10)	**C(15)**
10.	RC Slab	10 m	2-lane, 1-way	France	Bouteldja 2008		B(10)	B+(7)	B+(7)	**B(10)**

Strain gages were attached to longitudinal stiffeners on an orthotropic steel bridge in eastern France (Site 2) (Dempsey et al. 1999). The stiffeners were spaced 600mm apart, and spanned 4.62m between cross beams. The signals from stiffeners located beneath wheel lines were used as axle detectors, making this B-WIM installation the first NOR site. The strains in the longitudinal stiffeners were very sensitive to the transverse position of the trucks (measured using an infrared sensor), prompting the authors to implement a two-dimensional surface of influence lines. Reported accuracies were D+(20) for the conventional influence line, and C(15) using the 2D surface of influence lines.

Accuracy results from several BWIM sites are reported by Znidaric et al. (1999b). At the first site (Site 3 in Table 7), an integral slab bridge was analyzed using an experimentally-determined influence line but no other data processing enhancements with a resulting overall accuracy of D+(20).   The accuracy improved to B(10) when the same data was reanalyzed with the following enhancements:

- one calibration factor for tractor/trailers and a separate one for two-axle trucks,
- vehicle velocity and axle loads were optimized by minimizing the error between the measured and the calculated strain histories, and
- 4% of the B-WIM measured front axle loads was shifted to the following axles for all but two-axle trucks

The same authors analyzed two very similar bridges (Sites 4 and 5 in Table 7) that differed only in the amount of skew. The axle group and gross weight accuracies were B(10) or better for both bridges, demonstrating that acceptable accuracies can be obtained from a B-WIM installation on a skewed bridge.

Finally, the same authors analyzed B-WIM data from a bridge with a bump in the pavement (Site 6). Overall accuracy improved from E(40) to C(15) when lightly-loaded trucks (gross weights less than 20 kN) were removed from the data set. In a later paper (Znidaric et al. 2008), the authors show that dynamic amplification factors are much higher for lightly-loaded trucks than for heavily-loaded trucks.

Data from an integral slab bridge in Sweden near Stockholm (Site 7) was analyzed three different ways, (Quilligan et al. 2002). The first analysis, using a typical one-dimensional influence line, produced an overall accuracy of B(10). The second analysis used a two-dimensional surface of influence lines and the accuracy improved to B+(7). The final analysis included data from multiple presence events (two trucks running beside each other) which are typically excluded from weight calculations, and produced a very respectable accuracy of B(10).

Another integral slab bridge in Sweden (Site 8), this time near the Arctic Circle, was tested in summer 1997, winter 1998 and summer 1998 (McNulty and OBrien 2003). Accuracies reported for the three test periods were C(15), D+(20) and B(10), respectively. This was a 'blind' test, i.e., the static weights were withheld from the authors until the B-WIM calculated weights were returned to the test organizers.

A pair of short-span concrete bridges were instrumented in France (Sites 9 and 10) in the summer of 2005 with the SiWIM system (Bouteldja et al. 2008). The accuracies were generally good, ranging from C(15) to B+(7). Two lanes of a four-lane steel orthotropic bridge were instrumented with the SiWIM system in 2006. The accuracy was reported to not be as good as for the short slab bridges, due largely to the sensitivity of the instrumented longitudinal stiffeners to variations in the lateral position of truck traffic. Accuracy classifications were not reported for this bridge, due to the small number of trucks weighed statically. The authors plan to implement a 2-dimensional surface of influence lines with an updated version of the SiWIM system and expect accuracies ranging from C(15) to B(10).

B-WIM FOR TRUCK WEIGHT ENFORCEMENT

WIM data can be used in "real-time" to select heavy vehicles from the traffic stream for static weighing. Pre-selection allows static weigh crews to operate more efficiently and also does not penalize trucks which operate below legal limits by wasting their time. Without pre-selection,

weigh crews have to rely upon experience to select vehicles for static weighing and citation rates can be relatively low.

Pavement WIM Pre-selection

In the Netherlands, a multiple-sensor piezo-quartz system was used in the WIM-Hand and WIM-VID projects (Van Loo 2001) to identify overweight vehicles. Police used this data to identify the offending vehicles and to escort them to a static weigh station.

Pavement WIM is used as a pre-selection tool by many DOTs within the US in two ways. Mobile screening functions identically to a B-WIM pre-selection site. Data from the WIM system is transmitted to a weigh crew located downstream and the weigh crew uses the data to identify, pull over and weigh the trucks statically. Mobile screening is used in Alabama, California, Florida, Indiana , Michigan and Minnesota and North Dakota. The second method, fixed site screening, uses WIM in conjunction with fixed static weigh sites. The pavement WIM can determine which trucks are over or close to legal weight limits. Variable Message Signs then signal these vehicles to pull into the weigh station for compliance weighing, allowing other vehicles to pass without delay. This method is used by DOTs in California, Kentucky, and Washington. There are over 550 WIM sites in use across the US at present although not all these are used for enforcement (Krupa and Kearney 2009).

Accuracy Requirements

An accuracy class of C(15) or better has been suggested as being sufficient for pre-selection requirements (Jacob et al. 2000); an accuracy below this is deemed unsuitable. Weigh crews generally prioritize GVW for weight enforcement. B-WIM systems are generally significantly more accurate for gross weight than for individual axles.

Hidden System

B-WIM systems can be installed completely below the bridge deck, and are therefore not viewable by the passing traffic. The static weigh crew is generally positioned at a location downstream from the bridge, reducing the likelihood that truck drivers will make a connection between the bridge and the static weigh crew.

Although no weighing instrumentation is visible while crossing the bridge, systems set up for pre-selection generally require a camera to be mounted at the bridge site, which may arouse driver suspicion. Drivers of overweight trucks are known to make detours or to simply pull over and wait once alerted by other drivers of weight enforcement activity. Ideally, bridges selected for enforcement-related B-WIM should have lengthy detours to discourage the drivers of overweight vehicles from avoiding the bridge and/or weigh crew.

Communication with Weigh Crew

Once a vehicle has been weighed by the B-WIM system and determined to be overweight, it is essential that an accurate description be provided to the downstream weigh crew so that it can be pulled from the traffic stream for static weighing. One method is to transmit a photograph of the vehicle on the bridge via a cell-phone network. By considering the distance between the bridge and the static weighing location, an estimate of the arrival time can be made. The truck can then be easily identified using the photograph and information from the B-WIM system on axle configuration. The photograph and other B-WIM information can only be transmitted from the

B-WIM site to the weigh crew if cell phone data connections are possible at both the B-WIM site and the static weighing site.

An alternative method of using B-WIM data for pre-selection is to station a person at the bridge site while static weighing is taking place. When a heavy/overweight vehicle crosses the bridge, a note is taken of the vehicle type, color, and shape as well as the GVW and its timestamp. Vehicle information is then relayed to the weigh crew by CB radio or other method so that they can identify the correct vehicle to pull over and weigh.

SiWIM

The only commercially available B-WIM system currently available is SiWIM, which is manufactured and developed in Slovenia by CESTEL. SiWIM utilizes Moses' algorithm for determining GVW and axle loads of vehicles crossing the bridge. The system accommodates NOR and also allows a camera to be installed to take photographs of heavy vehicles. The system is easy to install once access to the underside of the bridge is provided. Installation of sensors and calibration of the system can be completed in one day allowing pre-selection to commence the following day. The SiWIM system consists of strain sensors, a cabinet which contains the system engine, a temperature sensor and optional extras such as camera and router (Znidaric et al. 2011).

CONCLUSIONS

B-WIM was first developed in the United States in 1979 by Fred Moses and George Goble as a means to weigh vehicles travelling over a bridge at full highway speeds. Similar systems were developed in Australia in the early 1980's, principally for culverts. Two European research initiatives in the late 1990's, WAVE and COST 323, supported a number of important B-WIM developments. One of the premier developments was the COST 323 accuracy classification for WIM systems. This allowed for the direct comparison of different B-WIM systems, setups and algorithms. The introduction of NOR was also a significant development because it eliminated the need for sensors on the road surface. B-WIM equipment is portable and can now be installed with zero disruption to traffic and with minimal visibility to drivers, significant advantages over pavement WIM installations.

It has been widely acknowledged by researchers that inaccuracies in measured vehicle weights are principally attributed to the dynamic oscillations of the vehicle and bridge. Much research has focused on developing methods and algorithms which can accurately account for these dynamic fluctuations. Research into dynamic algorithms has been conducted as part of the European initiatives but has not been implemented in a commercial system. Recent developments into MFI methods have produced promising results but to date these methods have been too computationally demanding to deploy in the field for real-time measurements.

B-WIM accuracy has steadily increased due to improved bridge site selection, sensor placement, and data processing techniques. To date, B-WIM installations have not achieved accuracies sufficient for direct enforcement of overweight vehicles, but several installations have achieved accuracies sufficient for pre-selection of overweight vehicles. Recent developments in B-WIM MFI methods show promise of achieving B-WIM accuracy sufficient for direct enforcement.

REFERENCES

Bouteldja, M., Jacob, B. and Dolcemascolo, V., (2008) 'Test of a B-WIM System on Integral and Steel Orthotopic Deck Bridges in France', in Proceedings of the 5th International Conference on Heavy Vehicles (ICWIM '08), pp. 205-213, Paris, France.

Bushman, R., Pratt, A., J., (1998) 'Weigh In Motion Technology – Economics and Performance' Presented at NATMEC 1998, Charlotte, North Carolina.

Carr, B. and Rizenbergs, R. (1971). Development of an Electronic Means of Weighing Vehicles in Motion.

Chatterjee, P., OBrien, E. J., Li, Y.-Y. and González, A., (2006) 'Wavelet domain analysis for identification of moving loads from bridge measurements', Computers & Structures, 84, 28, pp. 1792-1801.

Dempsey, A. Znidaric, A. and OBrien, E. (1998a), 'Development of a Dynamic Bridge Weigh in Motion Algorithm', in Proceedings of 5th International Symposium on Heavy Vehicle Weights and Dimensions, pp. 95-113.

Dempsey A., Jacob B., Carracilli J. (1998b), 'The use of instrumented orthotropic bridges for determining vehicle weights, dimensions and parameter, *Proceedings of the 5th International Symposium on Heavy Vehicles Weights and Dimensions*, Austrailian Road Research Board, Brisbane, Australia, pp. 188-209.

Dempsey, A., Jacob B., Carracilli J., (1999) 'Development and Experimental Testing of Orthotropic Bridge WIM for determining Axle and Gross Vehicle Weights' *Proceedings of the Final Symposium of the project WAVE*, Ed. B. Jacob, Hermes Science Publications, Paris, France, pp. 227-237.

Dolcemascolo V., Labry D. and Jacob B. (2002), "Accuracy Comparison of Two Multiple-Sensor WIM Static Weight Estimation Algorithms", in *Proceedings of the 3rd International conference on WIM*, eds. B. Jacob, B. McCall and E.J. OBrien, Orlando, Florida, May 13-15, pp. 147-158.

Dowling, J., González, A., OBrien, E.J., Walsh, B. (2010), 'Finite Element Model Updating using Cross-Entropy', *Bridge & Infrastructure Research in Ireland 2010*, Eds. N.A. Ní Nualláin, D. Walsh, R. West, E. Cannon, C. Caprani, B. McCabe, Cork Institute of Technology, pp. 17-24.

Epsco Inc and Michigan State Highway Department. (1961) Automatic Weighing of Vehicles in Motion and Collection of Traffic Data by Electronic Methods, Feasibility Study; for Michigan Project 52 F-26.

Goble, G., Moses, F., and Pavia, A., (1974), *Field Measurements and Laboratory Testing of Bridge Components*, Case Western Reserve University, Final Report, 126 pages.

Goble, G., Moses, F., and Pavia, A., (1976), "Application of a Bridge Measurement System", *Transportation Research Record No. 579*, Washington, D.C., pp. 36-47.

Ghosn, M. and Xu, Q. (1988), 'Estimating Bridge Dynamics Using the Weigh-In-Motion Algorithm' in *Transportation Research Record 1200, Department of Civil Engineering, The City College of New York*, New York.

González, A. (2010) *Development of a Bridge Weigh-In-Motion System*. Germany: LAP Lambert Academic Publishing AG & Co. KG., ISBN-10: 3838304160, 456 pages.

González, A. and OBrien, E.J. (1998) The Development of a Dynamic Bridge Weigh-in-Motion Algorithm *Pre-proceedings of 2nd European Conference on Weigh-in-Motion of Road Vehicles* Luxembourg, , pp.445-452.

González, A., Rowley, C. and OBrien, E. (2008) 'A general solution to the identification of vehicle interaction forces', *International Journal of Numerical Methods*, 753:335-354

Jacob, B. (Editor) (1999), *Proceedings of the Final Symposium of the project WAVE*, Hermes Science Publications, Paris, France.

Jacob, B.A. and OBrien, E.J., (1996) 'WAVE - A European Research Project on Weigh-in-Motion', *National Traffic Data Acquisition Conference (NATDAQ '96)*, Vol. II, ed. G. Knoebel, Alliance for Transportation Research, Albuquerque, New Mexico, pp. 659-668

Jacob, B. (2000), 'Assessment of the accuracy and classification of weigh-in-motion systems: Part 1 Statistical background', *Heavy Vehicle Systems, International Journal of vehicle Design*, Vol.7, No. 2/3, pp. 136-152.

Jacob, B., OBrien, E.J. and Newton, W. (2000), 'Assessment of the Accuracy and Classification of Weigh-in-Motion Systems: Part 2 European Specification', *Heavy Vehicle Systems, International Journal of Vehicle Design* , Vol. 7, Nos. 2/3, 2000, pp. 153-168.

Jacob, B., OBrien, E.J. and Jehaes, S. (Eds.) (2002), *Weigh-in-Motion of Road Vehicles: Final Report of the COST 323 Action*, LCPC Publications, Paris, 538 pp.
Jacob, B., Feypell-de La Beaumelle, V. (2010) 'Improving truck safety: Potential of weigh-in-motion technology', IATSS Research 34, pp. 9-15.

Jacob, B., and Feypell-de La Beaumelle, V. (2010) ‗Improving Truck Safety: Potential of Weigh-in-Motion Technology', IATSS Research 34, pp.9-15.

Kalin, J., Znidaric, A., Lavric, I., (2006) 'Practical Implementation of Nothing-On-The-Road Bridge Weigh-In-Motion System' 9th International Symposium on Heavy Vehicle Weights and Dimensions.

Kobayashi Y., Miki C., Tanabe A. (2004). 'Long-Term Monitoring of Traffic Loads by Automatic Real-Time Weigh-in-Motion', *Journal of Structural Mechanics and Earthquake Engineering*, JSCE, No.773, Volume 1-69, pp.99-111, (in Japanese).

Krupa C., Kearney T., (2009), 'Truck Size and Weight Enforcement Technology, Task 2 Deliverables – State of the Practice of Roadside Technologies' FHWA, 66 pp.

Law, S. S., Chan, T. H. T, Zeng, Q. H. (1997). 'Moving force identification: A time domain method', *Journal of Sound and Vibration*, 201, pp. 1-22.

Law, S. S., Chan, T. H. T., and Zeng, Q. H. (1999). 'Moving force identification: a frequency and time domain analysis', *ASME Journal of Dynamic systems, Measurement and Control.,* 12, pp. 394-401.

Law, S. S., Bu, J. Q., Zhu, X. Q., and Chan, S. L. (2004). 'Vehicle axle loads identification using finite element method', *Engineering Structures,* 26, pp. 1143-1153.

Law, S. S., and Fang, Y. L. (2001). "Moving force identification: optimal state estimation approach." *Journal of Sound and Vibration,* 239(2), pp. 233-254.

Lee, C.E. and Nasser, I. (1968). A Portable Electronic Scale for Weighing Vehicles in Motion. Research Report.

Machemehl, R., Walton, C.M. and Lee, C.E. (1975). Acquiring Traffic Data by in-Motion Weighing. *Transportation Engineering Journal,* **101** (4): 681-689.

Matui, S., El-Hakim, A. (1989), 'Estimation of Axle Loads of Vehicle by Crack Opening of RC Slab', *Journal of Structural Engineering*, JSCE, pp.407-418,(in Japanese).

McNulty, P., and OBrien, E.J. (2003), 'Testing of Bridge Weigh-In-Motion System in Sub-Arctic Climate', Journal of Testing and Evaluation, Vol. 31, No. 6, Nov., pp. 1-10.

Miki, C., Meta M., Murakoshi, J., Yoshimura S. (1987), 'Estimation of Weight of Moving Truck', *Bridge and Foundation Engineering,*1987-4, pp.41-45 (in Japanese).

Moses, F. (1979), 'Weigh-in-Motion System Using Instrumented Bridges', Transportation Engineering Journal, ASCE, 105, TE3, pp. 233-249.

Nordlin, E.F., Kubel, L., Bailey, A., (1969). *Vehicle Classifying Counter: Final Report,* Division of Highways, State of California, 44pp.

OBrien, E.J., Kealy, N.J., (1998) 'Development of a Novel Bridge Weigh-In-Motion System' in Proceedings of 5th International Symposium on Heavy Vehicle Weights and Dimensions, pp. 222-235

OBrien, E.J., Žnidarič, A. and Dempsey, A.T., (1999) 'Comparison of two independently developed bridge WIM systems', Heavy Vehicle Systems, Int. J. of Vehicle Design, Vol. 6, Nos 1 – 4, pp.147-161.

OBrien, E.J., Žnidarič, A., (2001), *Weighing-in-Motion of Axles and Vehicles for Europe (WAVE): Report of Work Package 1.2*, Slovenian National Building and Civil Engineering Institute (ZAG), Ljubljana, Slovenia.

OBrien, E.J., Quilligan, M.J. and Karoumi, R. (2006), 'Calculating an Influence Line from Direct Measurements', *Bridge Engineering, Proceedings of the Institution of Civil Engineers*, 159(BE1), Mar., pp. 31-34.

OBrien, E.J., González, A., Dowling, J. (2010), 'A filtered measured influence line approach to bridge weigh-in-motion', *Bridge Maintenance, Safety, Management and Life-Cycle*

Optimization, Eds. D.M. Frangopol, R.Sause & C.S. Kusko, Philadelphia, Taylor & Francis, pp. 953-960.

O'Connor, C. & Chan, T.H.T. (1988a), 'Dynamic Wheel Loads from Bridge Strains', *Journal of Structural Engineering*, ASCE, Vol. 114, No. 8, August, pp. 1703–1723.

O'Connor, C. & Chan, T.H.T. (1988b), 'Wheel Loads from Bridge Strains: Laboratory Studies', *Journal of Structural Engineering*, ASCE, Vol. 114, No. 8, August, pp. 1724–1740.

Ojio, T., Yamada K., Kainuma S., Obata T., Furuichi T. (1998), 'Estimation of Traffic Loads using Strain Recording in Orthotropic Steel Deck', *Journal of Structural Engineering*, JSCE, Vol.44A, pp. 1141-1151, (in Japanese).

Peters, R.J., (1984) 'AXWAY - A system to obtain vehicle axle weights', Proceedings 12thAustralian Road Research Board Conference, 12 , 1, pp. 17-29.

Peters, R.J. (1986), 'CULWAY - an Unmanned and Undetectable Highway Speed Vehicle Weighing System', in Proc. 13th AARB Conference, Australian Road Research Board, 13, 6, pp. 70-83.

Quilligan, M, Karoumi, R, OBrien, EJ. (2002) 'Development and testing of a 2-dimensional multi-vehicle Bridge-WIM algorithm' In: Proceedings of the third international conference on weigh-in-motion, pp. 199-208.

Rowley, C.W., Gonzalez, A., OBrien, E.J., Znidaric, A., (2008). 'Comparison of Conventional and Regularized Bridge Weigh-In-Motion Algorithms', *Proc. Int. Conf. on Heavy Vehicles (ICWIM5)*, Eds. B. Jacob, E. OBrien, A. O'Connor, M. Bouteldja, Wiley, pp. 271-282.

Rowley, C.W., OBrien, E.J., González, A. and Žnidarič, A., (2009) 'Experimental Testing of a Moving Force Identification Bridge Weigh-in-Motion Algorithm', Experimental Mechanics, Vol. 49, Issue 5, 2009, pp. 743-746.

Sanders, L., 'The History of Weighing' <http://www.averyweigh-tronix.com/main.aspx?p=1.1.3.4>, (Oct. 8, 2010)

Trott, J., and Grainger, J.(1968). *Design of a Dynamic Weighbridge for Recording Vehicle Wheel Loads*. Road Research Laboratory Report. Volume 219. Minsitry of Tansport. London.

Van Loo, F.J. (2001), *WIM-Hand Project, 1st Intermediate Report*, Rijkswaterstaat (Road and Hydraulic Engineering Division of the Dutch Ministry of Transport, Public Works and Water Management).

Yu L., and Chan, T. H. T. (2003). "Moving force identification based on the frequency-time domain method." *Journal of Sound and Vibration*, 261, pp. 329-349.

Zhu, X. Q, and Law, S. S. (2001). 'Orthogonal function in moving loads identification on a multi-span bridge.' *Journal of Sound and Vibration,* 252(2), pp. 329-345.

Žnidarič, A. and Baumgärtner, W., (1998). 'Bridge Weigh-in-Motion Systems — an Overview'. Pre-Proceedings of 2nd European Conference on Weigh-in-Motion of Road Vehicles, Lisbon 14-16 September. Luxembourg: European Commission, pp. 139-152.

Žnidarič, A., Dempsey, A., Lavric, I., and Baumgartner, W. (1999a) 'Bridge WIM systems without axle detectors', in Proceedings of the Final Symposium of the project WAVE, Paris, France, pp. 101-110.

Žnidarič, A., Lavrič, I. and Kalin, J. (1999b), 'Bridge WIM Measurements on Short Slab Bridges', in Proceedings of the Final Symposium of the project WAVE, Ed. B. Jacob, Hermes Science Publications, Paris, France, pp. 217-226

Žnidarič, A., Lavic, I. and Kalin, J., (2008) 'Measurement of Bridge Dynamics with a Bridge Weigh-in-Motion System', *Proc. Int. Conf. on Heavy Vehicles (ICWIM5)*, Eds. B. Jacob, E. OBrien, A. O'Connor, M. Bouteldja, Wiley, pp. 388-397.

Znidaric, A., Lavric, I., Kalin, J., and Kulauzovic, B. (2011), 'SiWIM Bridge Weigh-in-Motion Manual', Fourth Edition, ZAG Ljubljana.