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INTRODUCTION

Heavy trucks cause a great deal of wear and damage to pavements and bridges. There is a need for weight control to reduce the likelihood of illegally overloaded vehicles and to preserve the road infrastructure. Traditional weigh stations with static scales can not accommodate high volumes of truck traffic and Weigh-In-Motion (WIM) technology offers a solution to weigh trucks travelling at highway speeds automatically. WIM systems can pre-sort those trucks that are suspected of being overloaded to direct them to static scales, minimising unnecessary stops and delays for drivers. At the beginning of the 1990's, some European countries expressed a great demand for this technology in order to (Jacob 1999):

- Improve knowledge of traffic for economic surveys, statistics, road management and traffic monitoring;
- Improve the technical basis for pavement and bridge design and maintenance;
- Ensure fair competition in transport and road safety, by enforcing harmonised legislation of vehicle weights across Europe;
- Provide to government authorities the information necessary for a harmonised tax system.

However, vehicles in motion have constantly varying axle weights as a result of road roughness and vehicle dynamic properties. The variation from the static weight can be up to 100% and is commonly of the order of 20%. Hence, conventional Weigh-in-Motion (WIM) systems had limited accuracy for estimating static weights, in particular for legal purposes. European road authorities required more accurate and reliable systems to weigh vehicles in motion, preferably at low cost and under a wide range of environmental conditions. Large European research projects such as WAVE (**W**eigh-in-Motion of **A**xles and **V**ehicles for **E**urope) (Jacob et al. 2000) have taken place to effect a significant step forward in the development of WIM technology, specially in the fields of fibre optic sensors, multiple-sensor WIM and Bridge based WIM systems.

Bridge WIM (B-WIM) systems were initially introduced in the United States in the late 1970's (Moses 1979). Instrumented bridges can be used to determine the weights of vehicles at full highway speed. Generally, axle weights are obtained from the information supplied by strain gauges placed under the bridge deck and axle detectors on the road surface. Some B-WIM systems can obtain axle weights solely from strain measurements without any need for an installation on the road surface. As in road WIM sensors, dynamics is identified as an impediment to improvements in accuracy. In addition to the dynamics of the truck, the bridge and the interaction between both has been reported as a major potential for inaccuracy in B-WIM systems (O'Brien et al 1999b). However B-WIM offers the possibility of measuring the effect due to the dynamic wheel forces over an extended period of time and for different points of the bridge structure. This amount of information can be fully exploited to improve the estimation of static weights and gain information on the truck and bridge dynamic behaviour.

The principal objective of this thesis is the development of more accurate B-WIM systems through new algorithms. The sub-objectives have been:

- Numerical modelling of the dynamic vehicle/bridge interaction problem for a better understanding of the parameters influencing the bridge response.
- The implementation of a finite element technique to simulate the passage of a vehicle over a bridge.
- The collection of data at different B-WIM sites for testing the accuracy of a B-WIM system on the field.
- The collection of data in a B-WIM site during a period of two weeks and the development of software to process this data into traffic characteristics on a continuous basis.
- The theoretical testing of a number of B-WIM algorithms for different types of trucks, road profiles and bridge models.

Chapter 2 is devoted to the applications of Weigh In Motion data, as well as an introduction to Weigh In Motion systems. The use of WIM data for bridge and pavement applications, road planning and management purposes, and for the enforcement of illegally overloaded trucks is discussed. The basic types of WIM systems (bending plates, strip sensors and multiple sensor WIM) and their levels of accuracy are described.

Chapter 3 provides an explanation of existing Bridge Weigh In Motion algorithms. In recent years, Bridge weigh-in-motion systems have seen different approaches to the calculation of axle weights. Some efforts have concentrated on a better definition of the input variables to the static algorithm as defined by Moses (1979). Accordingly, influence lines have been corrected experimentally, signal filtering has been improved and the sensitivity of the algorithm to axle spacing and speed has been minimised through the application of optimisation techniques. Other research has focused on the development of a dynamic algorithm. The formulation and some accuracy results for these contributions are reviewed.

Chapter 4 describes the hardware and software involved in B-WIM systems. Various aspects of the installation are examined. Strain gauges/transducers or mechanical strain amplifiers can be used to measure the bridge flexure. From the point of view of axle detection, B-WIM systems can use sensors mounted in/on the road surface (pneumatic tubes, tape switches or low-grade piezo electric sensors) or in appropriate sites, strain readings can be used to identify axles (Free of Axle Detector systems). The Australian, Slovenian and Irish B-WIM systems are introduced.

Chapter 5 deals with the problem of dynamic modelling of a vehicle passing over a bridge. In B-WIM practice, vehicle loads can only be found through the measurement of the bridge response (i.e., strains). This chapter analyses the difficulties involved in determining applied forces by simulating the data available for a B-WIM calculation. The bridge is idealised as a prismatic beam, for which the differential equations of motion are solved by numerical methods. The truck has been modelled as a two-axle linear sprung body. The body is represented by a distributed mass subjected to rigid-body motions. Vertical displacements and pitching rotation are considered. Tyres are treated as linear elastic spring components. Linear spring and damping elements are used to simulate the suspension at each axle. The model takes account of the vehicle speed, dynamic behaviour of vehicle and bridge, and road roughness (generated from a power spectral density function). This four degree-of-freedom vehicle and continuous beam model offers an easy numerical implementation (In addition to reduced computer time and computer memory storage) for preliminary studies on the influence of different bridge, truck and/or road parameters on the dynamic response.

A more sophisticated eleven degree-of-freedom model developed and validated experimentally by Green et al (1995) is also briefly introduced. The results of this four-axle vehicle model will be used in a later chapter for testing the B-WIM algorithm. In Chapter 5, Green's models are analysed for two types of suspension: steel-spring and air-spring, and different road conditions (suspensions are treated as non-linear devices that dissipate energy during each cycle of oscillation).

The finite element method is covered in Chapter 6. It is obvious that a simple beam model can not represent two- or three-dimensional behaviour, particularly in the case of a moving vehicle with paths that are not along the centreline of the bridge. For those reasons, Chapter 6 describes a finite element technique that enables bridges to be modelled with plate and beam elements and to interact with two- or three-dimensional vehicle models. This sophisticated modelling allows for a large number of different parameters to be considered such as:

- Number of vehicles, their number of axles, speed, wheel path on the bridge and characteristics of each vehicle (including mass distribution, elements to model suspension and tyre, etc.).
- Characteristics of the bridge structure, such as the bridge geometry, support conditions, and mass and stiffness distribution.
- Pavement roughness prior to and on the bridge, and other singular large irregularities such as a joint.

A number of bridge finite element models are designed for theoretical testing of B-WIM accuracy. These three-dimensional models are a simply supported isotropic slab, two-span isotropic slab, slab with edge cantilever, voided slab deck, beam and slab, skewed bridge and a cellular bridge type. Some models incorporate end diaphragms that provide lateral support and greatly affect the lateral bending and torsional characteristics of the bridge. MSC/NASTRAN for Windows software was used to model vehicles and bridges. This software provides the capability to determine transient dynamic response. A program was developed in C++ to perform simulations of truck models crossing a bridge. The code generates the interaction conditions to be read by NASTRAN for any arbitrary one-dimensional or spatial bridge and vehicle finite element models. Simultaneous traffic events running in the same or opposite directions can also be specified. These simulations will be used to assess the accuracy of the BWIM algorithm in Chapter 9.

Chapter 7 is focused on the development of new algorithms for the calculation of weights in Bridge Weigh In Motion systems. Conventional static bridge WIM algorithms might not be very accurate due to vehicle dynamics, bridge vibration and dynamic interaction of the vehicle and the bridge. A least squares error minimisation approach is generally used to calculate the axle loads which give a best fit between theoretical and measured strains. This function has an averaging effect on the dynamic variation of the load and has been shown to be moderately accurate (O'Brien et al. 1999b). An approach to the dynamic problem could be the prior removal of the dynamic components of the signal. However, this is not always possible without also removing part of the static response. For example, low-pass filtering can remove frequency components of the static response at relatively high frequencies depending on the shape of the influence line and the truck axle configuration.

An alternative dynamic bridge WIM system based on a frequency spectrum approach is presented in this chapter. A bridge allows for the collection of a lot of readings and a good definition of the frequency components of the signal. This algorithm does not require any prior knowledge of the bridge influence line. Other algorithms have been developed in the time domain to solve the inverse problem of the bridge-truck interaction models described in Chapter 5. They seek to correct the deviation from the static weight that bridge and truck dynamics can introduce in the measured strain. The formulation described here uses theoretical bridge and truck dynamic models whose parameters can be estimated by minimising the difference between the predicted strain spectrum and the measurement spectrum. These algorithms are based on the mathematical solution for simple cases of moving loads on bridges (i.e. constant loads or sprung masses in an iterative process). Other algorithms are based on an approximate solution, i.e., modal decoupling as suggested by Dempsey (1997).

The dynamic approach is further extended in Chapter 7 with the use of multiple sensors. Bridge WIM systems had used sensors at one longitudinal location (normally at midspan) until recently, when Kealy and O'Brien (1998) extended the algorithm to the use of several sensors along the length of the bridge. This approach provides the complete distribution of varying axle forces as the truck traverses the bridge but it has limitations in the number of axles that can be weighed simultaneously due to the dependency of the equations relating applied load to measured strain. These limitations are overcome with further considerations on the treatment, number and location of the strain readings. Furthermore, calibration of a B-WIM system tends to be highly dependent on the properties of the truck used for the process. The sensitivity of the results to the differences in the properties of the truck being weighed and those of the calibration vehicle are also investigated.

Chapter 8 assesses field measurements from B-WIM systems, using data from experiments carried out on bridges in Ireland, Sweden, France and Slovenia. Each of these sites has different environmental, traffic and structural characteristics: short span skew bridge in Ireland, two-span integral bridge in Sweden, long span continuous box-girder in France and simply supported medium span in Slovenia.

In Delgany (Ireland), one vehicle of known weight is passed over the bridge several times at different speeds and small variations in lateral position on the road to calibrate the system. For any Bridge WIM system, based on static or dynamic principles, there is a difficulty in obtaining an accurate system calibration. In static terms, the calibration consists of determining an accurate influence line for the bridge. This is often determined by scaling and/or adjusting a theoretical influence line to give a best fit of measured to theoretical results for the calibration vehicle. For a dynamic algorithm, an attempt can be made to characterize the bridge in a similar way. A new calibration method based on the representation of the experimental record in the frequency domain is presented. The method allows for an easy adjustment to allow for uncertainties in such items as the sensor sensitivity, the shape of the unit response or the bridge boundary conditions.

For the first time, Bridge WIM data was collected to calibrate the Eurocode for bridge loading for Irish conditions (O’Brien et al. 1998b). A specific program was developed by the author for the purpose of processing the traffic data from road and strain sensors into vehicle velocity, classification and weights on a continuous basis. The effect of accelerating/braking forces on B-WIM accuracy is also analysed.

In Belleville (France), the performance of a B-WIM system is tested in a two-span bridge, 110 m long. The problem in this bridge is threefold: significant dynamics, the allocation of the truck along the bridge, and difficulty in identifying the effect of individual axles in a long bridge. All these factors are aggravated by the likely presence of simultaneous traffic events. Piezo-electric sensors were used as permanent axle detectors, and the bending of the bridge was measured with strain gauges glued to the steel stiffeners. An instrumented truck participated in the experiment.

The bridge in Luleå (Sweden) has a two-span reinforced concrete section, with a total length of 30 m. The Irish B-WIM system was tested at this site in extreme climatic conditions (minus 30 degrees Celsius). The instrumentation was composed of mechanical strain amplifiers, rubber tubes for detecting axles and data acquisition equipment. For the purposes of calibrating, two vehicles were passed over the bridge several times at different speeds with small variations in lateral position on the road. Finally, the multiple-sensor B-WIM algorithm was tested in a 32 m Slovenian bridge, where sensors were spaced longitudinally every 4 m. The load history for two vehicle configurations is represented.

In Chapter 9, simulations from Chapters 5 and 6 are used to determine the best algorithm for calculating the static weights of moving trucks. Truck configurations with three different loading conditions and speeds are crossed over different bridge finite element scenarios for testing. Additionally, the bridge response for a one-dimensional bridge model when traversed by three combinations of speed and weight for two-axle and four-axle trucks is provided from an independent source (Green, Queen's University, Kingston, Canada). The influence of bridge structural behaviour, sensor location, vehicle suspension and road profile on the performance of each algorithm is analysed. Accuracy results for different algorithms are given according to the classification system of the COST323 European Specification on Weigh-In-Motion of road vehicles.

The last chapter is devoted to final conclusions. Several appendices are also included at the end of the text, which facilitate the comprehension and application of the various theories included in the main text. They include definitions, specifications, graphs, tables, and mathematical treatments, as well as basic principles of data acquisition, signal processing, structural analysis and computer programs.