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CONCLUSIONS

10.1 INTRODUCTION

The purpose of this research has been to increase the accuracy of B-WIM systems by improving the algorithm used for weight calculation. Considerable progress has been made in data acquisition hardware and software. This advance in data acquisition technology has allowed the measurement of voltage from axle detectors and a lot of strain sensors with good resolution and high scanning rates. Software has been developed to process this voltage information into vehicle classification and weights on a continuous basis.

Strain is the result of all axle forces that are on the bridge. On the one hand, this record can make it difficult to distinguish the contribution of each axle at each instant. On the other hand, a long continuous record of the whole truck weight is available. Hence, B-WIM systems will generally tend to be more accurate for calculating gross weights than axle weights. Inaccurate assumed characteristics for influence lines, bridge and vehicle dynamics, etc., have been shown to be sources of error for the traditional static B-WIM algorithm. An accurate separation of dynamic and static components is difficult to establish even at relatively high frequencies. The frequencies at which statics and dynamics are mixed together will depend on the vehicle speed, axle configuration, bridge length, stiffness and natural frequency. New B-WIM algorithms have been developed to overcome limitations derived from the bridge-vehicle interaction.

The accuracy of any pavement WIM system is influenced by two factors: vehicle dynamics and the pavement. The WIM system should be such that the road type would be the main limiting factor (COST323 1997). However, as individual pavement WIM sensors can only measure the wheel load for a very short period of time, the dynamic characteristics of the truck can only be estimated from its scant information. Attempts are made by multiple-sensor pavement WIM systems (MS-WIM) to incorporate truck dynamics in their algorithms through the use of many sensors and instantaneous readings. A similar approach has been adopted here for B-WIM. If, instead of using only one longitudinal location, a multiple-sensor B-WIM system is employed, the history of axle loads along the bridge can be described. Compared to pavement MS-WIM systems, a B-WIM system allows for a continuous measurement of the applied wheel forces, but the part of the measurements due to bridge damping and inertial forces or due to truck forces needs to be quantified. Additionally, the use of several sensors can have different B-WIM applications:

- Determination of axles, spacings and speed in a FAD (**F**ree of **A**xle **D**etector) system.
- Improvement in accuracy over traditional algorithms based on one sensor location.
- Better knowledge of bridge structural behaviour and truck dynamics.

B-WIM algorithms that take into account the dynamic as well as the static response of a bridge to a passing truck have also been introduced. Some features of these algorithms are the calculation of a theoretical total response instead of purely the static one, the consideration of more strain sensors and the application of best fitting techniques in the frequency domain.

10.2 RESULTS

The accuracy of different B-WIM algorithms has been analysed with data from trials in the field. Unless otherwise specified, the axle of a group criterion is not considered when giving overall accuracy as this is not required for B-WIM systems in the COST323 specification. Due to the limitations in the number of trucks and bridges used in the experiments, numerical and finite element techniques have been developed to simulate B-WIM data and further evaluate the performance of these algorithms.

A vehicle modelled as a linear discrete mass-spring-damper system moving on a beam has revealed the influence of the calibration truck parameters on B-WIM accuracy. A general finite element formulation for the solution of the bridge-vehicle dynamic interaction problem has also been presented. It is based on a Lagrange multiplier technique. Simulation results were in agreement with other numerical methods. This formulation is applicable to any vehicle and bridge finite element model, and it considers the bridge pavement as a random surface irregularity. There is no limitation concerning the complexity (number of degrees of freedom) of the bridge structure and vehicle model to be analysed. These theoretical models have made possible the study of alternative arrangements of strain sensors.

10.2.1 Experimental Results

A novel calibration procedure for determining the curve to be taken as reference in a static/dynamic algorithm has been introduced. This method is based on the spectrum of the measured signal and it has been used to calibrate B-WIM data from experiments in Ireland, Sweden, France and Slovenia. It is proven to be more accurate than other calibration methods based on theoretical models. Therefore, it has the advantage of adjusting boundary conditions, structural response and sensor sensitivity more directly than other experimental adjustments based on the time domain. All records/influence lines can be related to a period of time from the instant that the first axle of the vehicle hits an axle detector prior to the bridge to some instant where there is certainty of the vehicle having left the bridge. There is no need to know the exact point when the bridge starts to bend.

In Delgany, testing took place in two periods: May and July 1997. The bridge is 30º skew, 16 m long and simply supported. Overall accuracy of C(15) and E(40) are obtained with the new calibration method in May and July respectively. The criterion of gross weight remains in A(5) in May and decreases to B+(7) in July. The change in accuracy from May to July is attributed to the installation and/or sensitivity of the sensors, as a few sensors had to be replaced after the first test. For the same tests, overall accuracy decreases to E(55) in May and E(60) in July if using a theoretical beam model. Furthermore, overall accuracy by the experimental approach increases to A(5) in May if full repeatability conditions are considered. This accuracy is only C(15) when using a wide range of speeds due to the influence of a 4 Hz hardware filter.

In Luleå (June 1997), an overall accuracy of D+(20) is obtained if using one influence line and limited reproducibility conditions. However, A(5) is obtained if using full repeatability conditions at speeds of about 80 km/h and a 6-axle truck configuration. If the runs of a 3-axle truck at about 80 km/h are also taken into account, overall accuracy decreases from A(5) to B+(7). As in Delgany, the consideration of more truck configurations and speeds introduces an error due to the 4 Hz hardware low-pass filter applied in these experiments. Filtering removed not only dynamics, but also part of the static bridge response. The smoothing action of the filter depends on the truck configuration, vehicle speed and the shape of the influence line, and its use in signal processing should be restricted as much as possible (i.e. to post-processing, where original data can be recoverable).

A dynamic algorithm based on one longitudinal location has been tested in a long span bridge in Belleville. The bridge is a continuous two-span bridge of about 50 m per span. The section is made of a concrete slab and steel box. Longitudinal bending was measured at midspan of the first span and an accuracy class B(10) was obtained for gross weight in full repeatability conditions. Individual axle weights could not be estimated accurately as the vehicle acts as a whole concentrated load on such a long bridge. However, transverse bending of the concrete slab is more important and localised for this bridge than longitudinal bending of the steel box (more similar to a beam response), and its application in B-WIM systems could lead to more accurate results. A two-dimensional algorithm that allows for transverse position of the truck appears to be necessary if transverse bending is to be used for weight calculations in the near future.

The multiple-sensor B-WIM algorithm has been analysed with data from a bridge in Slovenia. Each section has been calibrated separately and a load history has been reproduced for each axle along most of the bridge length. Only those instants when an axle enters or leaves the bridge do not qualify for an instantaneous calculation due to rounding errors. The record offers an instantaneous solution with small oscillations around an average value very close to the real static axle weight. These oscillations and inaccuracy increase with a higher number of axles on the bridge. The presence of more axles requires more instrumented sections on the bridge to maintain an acceptable level of accuracy. Hence, the MS-BWIM system is not recommended in medium to long span bridges.

10.2.2 Theoretical Results

When the criterion of axle of group is not considered, the criterion of single axle is generally the one determining the overall accuracy. The results for this criterion in the finite element simulations are summarised in Table 10.1. The multiple-sensor algorithm is the most accurate, except for the central support location in two-span bridges, where a static algorithm based on one sensor location can be slightly more accurate. This is due to the absence of significant dynamics at this location. The dynamic algorithm cannot compete with the static algorithm, except for the longitudinal bending at midspan of a two-span isotropic slab and voided slab deck. Though the multiple-sensor algorithm appears to be more accurate in most of the cases, it also requires a more expensive installation. It is clearly necessary to determine if the levels of accuracy required by the user can be achieved with a simpler solution.

Table 10.1 - Accuracy results for single axle criterion

Bridge type	Len. (m)	Freq. (Hz)	One longitudinal location algorithms		Static Multiple-Sensor
			Static	Dynamic	
Beam model	30	3.33	E(45)	E(65)	B+(7)
Isotropic Slab	16	4.51	C(15)	C(15)	A(5)
Two span isotropic slab	37	4.18	D+(20) midspan A(5) central support	B(10)	A(5)
Slab edge cantilever	20	4.80	B(10)	C(15)	A(5)
Voided slab deck	25	3.80	D(25)	C(15)	C(15)
Beam and slab	20	6.13	B+(7) beam B+(7) longit. slab A(5) transv. slab	C(15)	A(5)
Skew	15	7.41	E(50)	E(45)	-
Two span Cellular	62	2.95	C(15) longit. midpan B+(7) trans. midspan A(5) central support	C(15)	C(15)

In addition to simulations generated by the author, Green has provided data to test the accuracy achieved by each algorithm. Static weights were withheld from the author until after submission of the calculated WIM results. The bridge is idealised as a 30 m long simply supported beam. The dynamic properties of the bridge are derived from strains caused by a two-axle linear sprung vehicle used for calibration. Then, four-axle truck models (nonlinear suspension elements), validated experimentally, are used to test accuracy. Two different types of road profile and suspension were used. Results are summarised in Table 10.2.

Table 10.2 – Accuracy classification for Green's simulations

Road profile	Criterion	One longitudinal location algorithms		Static multiple-sensor
		Static	Dynamic	
Smooth	Single axle	E(45)	E(65)	B+(7)
Smooth	Axle group	C(15)	E(30)	A(5)
Smooth	Gross weight	A(5)	B+(7)	A(5)
Rough	Gross weight	C(15)	E(50)	E(30)

In smooth road conditions, the multiple-sensor algorithm is the most accurate with B+(7) overall accuracy, and A(5) for the gross weight criterion. Accuracy by the static algorithm based on one longitudinal position is also A(5) for gross weight. The dynamic algorithm is not able to match the total strain as accurately as the static and it only reaches B+(7) for gross weight. It has been seen that B-WIM accuracy decreases for steel suspensions as bridge dynamic response is more important. In rough road conditions, the static algorithm achieves C(15) for gross weight, while the results for all other criterions and/or algorithms fall in class E.

10.3 DISCUSSION

Speed and axle spacings have been found to be significant sources of inaccuracy in the past. These parameters are the result of a direct measurement in the field. The improvement in axle detection hardware and the application of optimisation techniques to allow for errors in axle spacings and speed have reduced their influence on final accuracy noticeably. However, even though both parameters were totally accurate, this thesis has revealed that other parameters can produce very important errors. These are parameters related to the dynamic excitation of the bridge. The level of this excitation will depend on the truck mechanical characteristics and the conditions of the road prior to and on the bridge. Rough road profiles result in very poor results for any existing B-WIM algorithm. In this situation, only the traditional static B-WIM algorithm can provide reasonable results for gross weight. It is felt by the author that when bridge dynamics are highly excited, the fitting technique carried out by the traditional algorithm is more accurate than trying to model the total strains. Additionally, a truck with the same axle weights could result in a very different bridge response depending on their mechanical parameters. So, steel suspensions are estimated less accurately than air suspensions, as they are not as heavily damped. It has also been seen that the traditional static B-WIM algorithm generally achieves reasonable results in gross vehicle weight regardless of the accuracy in individual axle weights. It looks as if similar levels of gross vehicle weight develop similar levels of total strain energy, and Moses' approach identified this energy.

The implementation of a static B-WIM algorithm is easier than a dynamic B-WIM algorithm. DB-WIM can only be justified in bridges with a smooth road profile, low natural frequencies and a high bridge dynamic component. For example:

- If the bridge is too short, the strain response does not exhibit a sufficient number of dynamic oscillations to compensate each other. In this case, the DB-WIM algorithm based on one longitudinal location can offer a better solution. However, it is necessary to check that the dynamic bridge model approximates the measured strain well. A number of truck configurations representative of the traffic should be employed to ensure that the assumptions of the model are correct.
- DB-WIM might give a more accurate result when the total response is strongly influenced by speed. The maximum bridge response occurs for some pseudo-frequencies of the vehicle. An increase in the bridge response can also take place when the wheels vibrate in phase resulting in a higher total dynamic component. This phenomenon is more important at some speeds and a simple dynamic model can allow for this variation in the strain response better than a static approach.

In bridges with high natural frequency and low dynamics, a static B-WIM algorithm should be used. If a high level of accuracy is required, a static multiple-sensor B-WIM algorithm (MS-BWIM) can improve accuracy in individual axle weights over a single-sensor algorithm very significantly. However, there is still a need to analyse the number and location of sensors that guarantee a better instantaneous solution. If the bridge has a long span, MS-BWIM might require an excessive number of sensors and other possibilities such as the measurement of transverse bending should be considered.

There are cases where the static B-WIM algorithm is more accurate than MS-BWIM, i.e., in the central support location of a two-span bridge. It is obvious that, if the response of a bridge were purely static, the traditional B-WIM algorithm would be totally accurate. As the response of the bridge differs from the static, the traditional B-WIM algorithm loses accuracy. In the case of bending at the central support, the dynamic excitation at this point is very small compared to the static component and the traditional B-WIM algorithm is still very accurate. As the multiple-sensor algorithm considers new locations, which are not as close to the static answer, the final accuracy might not be as good as using only measurements at the central support.

Regardless of the algorithm, accuracy of Bridge WIM systems is expected to improve in bridges with a minimum dynamic response, this is, with a natural frequency out of the truck frequency range and/or with smooth surface profiles. Bridges generally vary in natural frequency from 1 Hz to 15 Hz. Short span bridges are more likely to match the axle hop frequency while longer bridges might couple with the vehicle body frequency (1.5 to 4.5 Hz). In any case, there is often a dynamic amplification that will decrease the accuracy of a Bridge WIM system. In the author's opinion, an improvement of the actual levels of accuracy can be achieved by feeding a database with strain recorded for different truck configurations. Then, each truck type could be calibrated in a different way according to the vehicle classification and characteristics of the bridge response. Axle spacings and speed are a reference for the first classification of the vehicle. A second classification of the vehicle can be established from the amplitude of the dynamic oscillations, resulting from the bridge-truck interaction. A detailed study of these curves will reveal if the separation of the static/dynamic truck components can be done more accurately.

10.4 SUGGESTIONS FOR FUTURE RESEARCH

In order to examine the influence of dynamics on B-WIM systems, the author developed a bridge-truck dynamic interaction model. There are a lot of aspects of this model that can be further improved for testing of B-WIM systems. For example: the modelling of the tyres, assumed to remain in contact with the bridge surface and the approach at all times, the vehicle suspension, represented by a simple linear spring in parallel with a viscous damping element, or the spectral description of the road profile, defined uni-dimensionally. Field tests are also necessary for experimental validation. The COST323 specification on WIM (Appendix B) indicates some characteristics of the road profile as an indication of the accuracy that might be achievable in a WIM site. However, this classification is not enough for B-WIM, as it does not allow for the presence of a large road irregularity prior to or on the bridge (i.e., the joint), and neither does it consider the influence of the bridge structural behaviour. Accurate simulations of a truck crossing over a bridge will allow researchers to predict what accuracy a Bridge WIM system might achieve depending on the bridge type and road conditions before installing a system in the field.

The weight of a steer axle is usually less than the static weight for a moving vehicle as a result of drag and friction effects. This reduction must be quantified and it should be taken into account during calibration. Higher calibration methods treating vehicles according to their type, weight and type of axle will further improve B-WIM accuracy. More progress is also expected in the area of Free of Axle Detector systems, a very promising technology that does not require any sensor on the road.

All B-WIM research to date has concentrated on a single truck event. However, bridges with high traffic density or long span structures are likely to be traversed by more than one vehicle simultaneously. The performance of B-WIM systems when weighing simultaneous traffic events needs to be tested in the near future. An algorithm purely based on one longitudinal location would have a lot of difficulty to determine which value corresponds to each vehicle (e.g., two axles of different vehicles entering the bridge simultaneously at the same speed). Thus, the problem of multiple presence of vehicles should be tackled with a two-dimensional MS-BWIM algorithm. If there are two lanes involved in the problem, this algorithm needs to allow for two different influence lines contributing to the total strain: one due to a unit axle running over one lane and another due to a unit axle running over the other lane. The theoretical basis for this algorithm has been established. A dynamic model of more than one truck on a bridge can be used as a tool for preliminary studies.

The B-WIM algorithm can be further improved by the consideration of axle loads as random stochastic processes. The randomness of the applied axle load is a result of the random variability of the initial conditions at the instant the axle arrives on the bridge, the random motions of the vehicle due to the random roadway unevenness, etc. Based on theoretical simulations or experiments (i.e., by using an instrumented truck), a correlation between the statistics of the moving load and the measured strains could be established. The spectral density of the generalised strain might be expressed as a function of the spectral density of the generalised force. The statistical characteristics of measured strain can be calculated directly, and work on the solution of the inverse problem (statistical characteristics of input loads) might result in a significant improvement in accuracy for B-WIM systems. The use of pattern recognition techniques and artificial neural networks can also be incorporated into B-WIM calculations. All of these areas of research could lead to the identification of truck mechanical characteristics (apart from static weights) through a B-WIM system.