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Monitoring of changes in bridge response using Weigh-In-Motion systems

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Abstract. Weigh-In-Motion (WIM) and Bridge Weigh-In-Motion (B-WIM) are systems that allow obtaining the axle weights of road vehicles in motion, at normal traffic speeds. While WIM employs sensors embedded in the road pavement, B-WIM use the strain recordings of a bridge to infer the traversing vehicle axle weights. Both systems have been heavily improved over the past decades, and commercial versions are currently in operation. The two main applications of these systems are: (1) to assess the traffic loading on the infrastructure, and (2) to enforce the maximum weight limits.

This paper suggests a novel application of these two systems to identify changes in bridge stiffness. It requires the bridge to be instrumented with a B-WIM system and a WIM system nearby. The principle is to use both systems to evaluate thegrossweight of vehicles passing over the bridge and correlate theirpredictions. Changes in correlation of the predicted axle weights over time will indicate either structural damage or faulty sensor. A finite element model of a coupled vehicle-bridge system with different damage scenarios is used to test the approach numerically. Vehicle mechanical properties and speeds arerandomly sampled within aMonte Carlo simulation. Results show how correlation changes as damage increases and how this correlation can be employed as a damage indicator.

Introduction

WIM systems comprehend a wide range of technologies that allow estimating wheel weights and axle spacing of road vehicles moving at full speed. WIM systems can be pavement-based or bridge-based. Pavement-based WIM systems include pressure cells, bending plates and inductive loops, among others, and are located on the road surface or embedded in the pavement generating the signals that after some manipulation will provide the desired information. The accuracy of the weight estimates depends on the quality and width of the weighing sensor and on the unevenness of the road profile. Since its appearance in the 1950's, sensitivity and accuracy have largely been enhanced (i.e., through the use of multiple-sensor WIM arrays on smooth profiles that can reach enforcement accuracy levels) and is nowadays a technology used worldwide [1].

Bridge-based WIM systems, or B-WIM,use the structure's response to estimate the vehicle's load distribution. Generally,strain gauges record the deformation of the bridge while the vehicle of interest is traversing the structure. The original idea, first introduced by Moses in 1979 [2], is based on the concept of influence line which can be obtained on-site using a vehicle of known speed, axle spacing and weights [3]. The algorithm searches for the load distribution that best fits the recorded response by minimizing the error with an assumed theoretical response. B-WIM tends to predict gross vehicle weights (GVWs) more accurately than individual axle weights due to the difficulty to separate the contribution of each individual axle to the global response [4]. Accuracy of the B-WIM system depends greatly on the length of the bridge and the vehicle's axle spacing. Stiff short straight spans (i.e., culverts or integral bridges) are best suited for B-WIM purposes [1]. However, many improvements have beenincorporated to this technology over the past decades [5] which increased the popularity of B-WIM and allowed to successfully implement it in other bridge sites.

The original aim of WIM technology was todetect excessively loaded road traffic and enforce legal axle weights as traffic travels at full speed. Then, the enormous amount of information on the traffic's characteristics provided by WIM has been further used for the development of accurate site-specific road traffic models, which in turn are used for probability based structural assessment.This paper proposes a novel application of pavement-based (installed near the bridge to be investigated) and bridge-based (installed on the bridge under investigation) WIM technology to assess the structural integrity of a bridge. The idea is numerically tested here using a Vehicle-Bridge Interaction (VBI) simulation model. A simple correlation of predicted vehicle weights between pavement-based WIM and B-WIM shows a clear correspondence with local stiffness reduction in bridges. Furthermore, it is demonstrated that the proposed method is more sensitive than the standard approach of tracking changes in the structure's modal frequencies. From this point forward, the abbreviation WIM will be used to refer to pavement-based WIM systems exclusively.

Simulation Model

The bridge is modelled as a fixed-fixed Euler-Bernoulli beam using a finite element discretization. This model is representative of a statically indeterminate structure (to some extent similar to the response of a culvert or integral-type bridge). The structure's properties are listed in Table 1. Fig. 1 shows a sketch of the beam and the location of the three B-WIM strain locations employed in the calculations. Additionally, damage is modelled by reducing the stiffness of one particular element of the beam at the desired location. The beam is discretized using 100 elements, thus making each element and the damage size equal to 10 cm. This investigation considers two locations of damage (¼ and ½ span) and four damage magnitudes (0, 25, 50 and 75 % stiffness reduction).

Table 1: Beam model properties

Description	Value
Length	10 [m]
Mass per unit length	18750[kg/m]
Young's modulus	$3.5\ 10^{10}$[N/m^2]
Section moment of inertia	0.1609 [m^4]
Damping	3 [%]
Natural frequency	19.5177 [Hz]

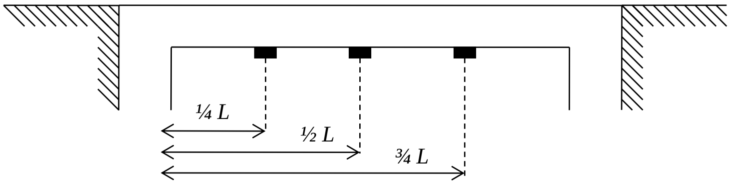

Fig. 1: Bridge Sketch

The vehicle model is a 4-DOF system as illustrated in Fig. 2. The main body and tyre massesare connected to each other and to the road profile by spring and dashpot systems. This model is simulated running over a Class A road profile [6] of 100 m length before arriving to the bridge to allow for the system to reach dynamic equilibrium. Once on the structure, thevehicle and beam models are solved iteratively to obtain the response of the coupled system. Further details on the solution of the integration of the equations of motion can be found in [7].

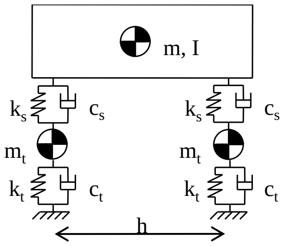

Fig. 2: Sketch of vehicle model

Basic Principle of the Proposed Bridge Health Monitoring System

The periodic measurement ofmodal parameters such as frequencyis a common approach in bridge monitoring. Permanent changesin the first natural frequency of the beam might indicate severe damage of the structure. However, temperature affects the recorded frequencies largely (this requires the simultaneous monitoring and correlation of both frequencies and temperatures) and the influence of local damage on the first natural frequency depends on the damage location and is relatively small. Fig. 3 shows frequency variations for the beam described previously, with damages located near ¼ or ¾ of beam's length. These damages lead to hardly noticeable changes in the main frequency of vibration of the bridge.

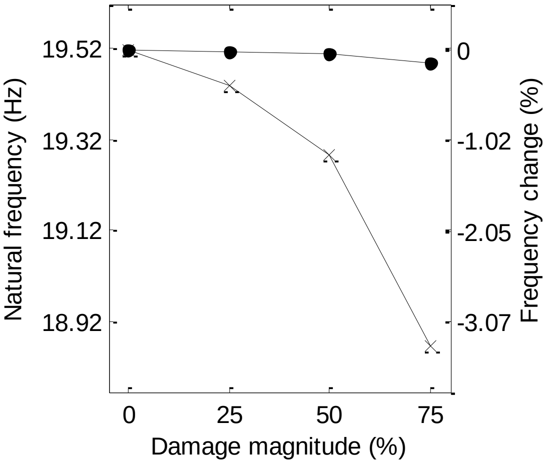

Fig. 3: Beam 1stnatural frequency for different damage magnitudes; damage location at L/4 (Dots) and L/2 (Crosses)

This paper proposes a new alternative for assessing damage in short to medium-span highway bridges.The principal idea is to detect damage of a structureby comparing the predictions in GVWfrom WIM and B-WIM systems. Both systems will estimate the GVW with random accuracy due to noise, sensor accuracy, dynamic effects and vehicle characteristics. However the changes in average predictions correlation between both systems can be used as a good indicator of the structure's health.

The WIM sensors aresimulated here in the approach to the bridge. In the numerical model, the vertical contact force of the vehicle with the pavement is taken as the WIM reading.In practice, the system will be calibrated to cater for bias of the WIM system due to the unevenness of the site. This WIM reading does not predict static axle weights exactly due to thevehicle oscillationsinduced by the particular profile roughness before the WIM sensor. The relative error of the predicted vehicle GVW by the WIM system, A_{WIM}, can be defined as in Eq. 1.

$$A_{WIM} = \frac{GVW_{WIM} - GVW}{GVW}. \tag{1}$$

Similarly, the relative difference in prediction of GVW by the B-WIM and WIMsystems can be defined as in Eq. 2. This correlation parameter between predictions of systems will prove to be a good indicator for detection of local bridge stiffness reduction.

$$A_{BWIM} = \frac{GVW_{BWIM} - GVW_{WIM}}{GVW_{WIM}}. \tag{2}$$

Fig. 4 shows the A_{BWIM} in the case of single moving load for various sensor and damage location. For each damage location a single moving load is modelled traversing a beam with a local stiffness reduction of 50%. Then the GVW estimates are computed for both WIM systems which give the presented A_{BWIM} in Fig. 4. To obtain a general idea of the influence of the damage on A_{BWIM}only the static component of the bridge response is considered in Fig. 4, in order to disregard other inaccuracy sources such as dynamic oscillations, (i.e., A_{BWIM} = 0% if the structure remains healthy). Results considering the dynamic contribution will differ for every profile or vehicle considered, and are analysed in further sections. Fig. 4clearly shows that every sensor features very small or zero changes in A_{BWIM} for some damage locations. As a result, the combination of the information of three sensors is necessary to prevent the existence of blind spots. Using various strain gauges along the beam span is common practice in modern nothing-on-road B-WIM systems [8].

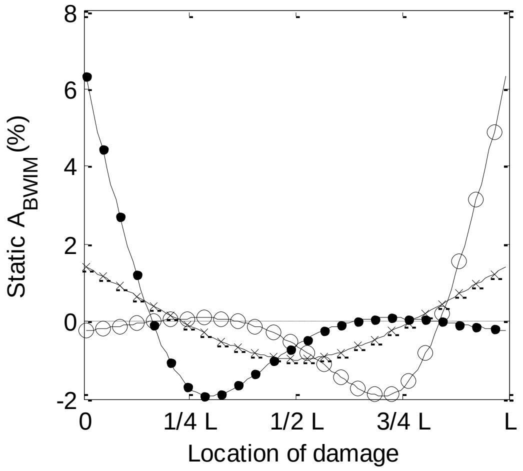

Fig. 4: Correlation parameter A_{BWIM} considering only the static component of the response for a 50% local stiffness reduction; for strain gauges at ¼ L (Dots), ½ L (Crosses) and ¾ L (Circles).

B-WIM systems basically try to find the optimum fit of the structure'sstatic response to the recorded dynamic response based on the concept of influence line, linearity and superposition. The magnitudes of the weights that provide a best fit give the estimate of the vehicle's weight distribution among axles. In the case of a healthy structure, the predictions in GVW are not exact mainly due to the dynamic contribution to the bridge response.In this regard, modern B-WIM systems are able to improve accuracy by filtering a significant part of the dynamic component before carrying out the fitting process. For a structure with a localised loss of stiffness, the structure's behaviour and the influence line change slightly. For example, Fig. 5 shows the influence lines due to a 10 kN loadfor healthy and damaged structures at two sensor locations. For the damaged scenarios, a severe 90% stiffness reduction was used to clearly visualize the differences between both curves.

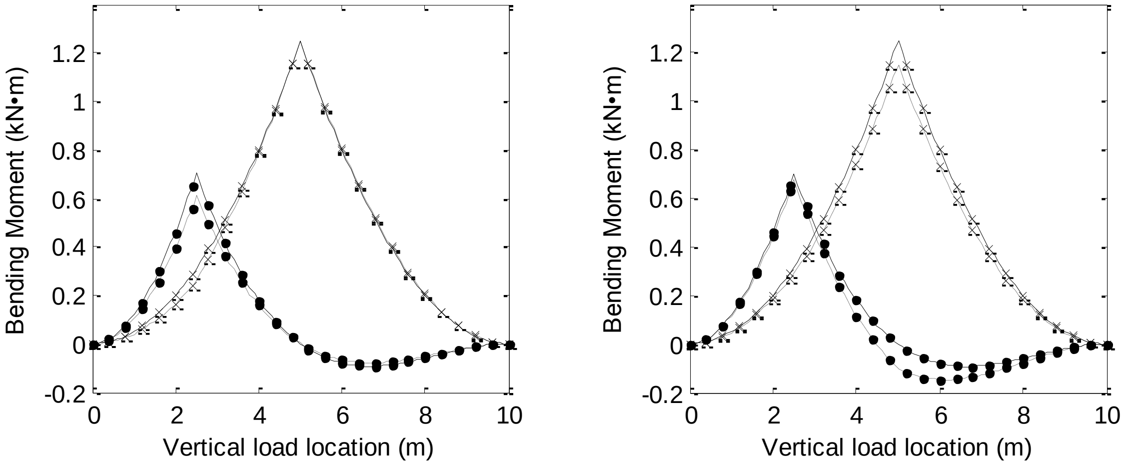

Fig. 5: Bending Moment influence line for healthy (solid line) and 90% reduced stiffness (dashed line); for sensor located at L/4 (dots) and L/2 (cross). a) Damage at L/4 b) Damage at L/2

Even though the differences presented in Fig. 5 are small, they are sufficient to assess the presence of damage. Therefore, when a B-WIM system is installed on a healthy bridge, a particular influence line is obtained during the calibration process. Eventually,when a local damage occurs, the system continues estimating GVW based on the healthy influence line. The average correlation factor(A_{BWIM}) will change indicating the existence of a possible damage.

Testing of Multiple VBI Scenariosusing Monte Carlo simulation

To validate the proposed idea, the authors implement the described model within a Monte Carlo scheme. Over 200.000 runs are simulated for 5 different Class A profiles, 2 damage locations (¼ and ½ L), 4 levels of damage severity (0, 25, 50 and 75% stiffness reduction) and random vehicle properties.

Table 2 lists therange of vehicle properties used in the simulation that can be found in the literature [6], and were sampled using a uniform random distribution. Fig. 6 shows the probability distributions for each of the vehicle's natural frequencies as a result of the random selection of the properties in Table 2. The firstand second natural frequencies are associated to the body mass vertical displacement and the pitch respectively. The other two are higher frequencies associated to each wheel's vibration.

Table 2: Range of vehicle properties for Monte Carlo simulation

Property	Name	Unit	Minimum	Maximum
Body mass	m	[kg]	$5\cdot10^3$	$2\cdot10^4$
Body Moment of Inertia	I	[kg·m^2]	$80\cdot10^3$	$200\cdot10^3$
Suspension Stiffness	k_s	[N/m]	$0.5\cdot10^6$	$2\cdot10^6$
Suspension damping	c_s	[N·s/m]	$5\cdot10^3$	$20\cdot10^3$
Tyre mass	m_t	[kg]	$0.5\cdot10^3$	$2\cdot10^3$
Tyre stiffness	k_t	[N/m]	$0.5\cdot10^6$	$20\cdot10^6$
Tyre damping	c_t	[N·s/m]	$5\cdot10^3$	$20\cdot10^3$
Axle spacing	h	[m]	5	5
Velocity	v	[km/h]	50	120

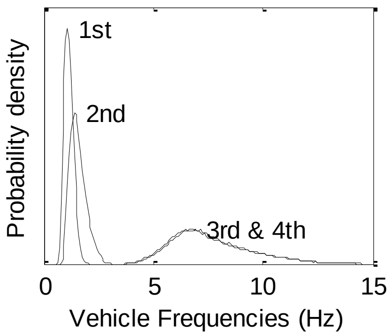

Fig. 6: Vehicle frequencies distributions from the Monte Carlo simulation; corresponding frequency indicated on the figure

First, the results of the Monte Carlo simulation at the WIM sensor are analysed.As expected, the WIM accuracy depends greatly on the local shape of the profile prior the sensors. This can be observed in Table 3 that gives the statistical variations of the average A_{WIM} for each profile. The mean results are significantly different but the variation, i.e., the standard deviation, is fairly similar for all five profiles. The simulation gives WIM errors similar to those obtained on on-site WIM sensors, which are usually within ±20% or smaller the better the road profile.

Table 3: Mean (μ) and standard deviation (σ) of WIM relative error (A_{WIM}) for various road profiles.

Profile number	μ A_{WIM}	σ A_{WIM}
1	4.69	5.22
2	-2.98	4.34
3	3.67	5.42
4	2.00	5.57
5	0.34	4.69

As for WIM, the accuracy of B-WIM also depends on the particular profile. This can be observed in Fig. 7that shows relative differences between WIM and B-WIM predictions for 5 profiles considering various degrees of damage located at ½ L of the beam. Any particular profile features a specific A_{BWIM}in the case of a healthy structure andas damage increases, A_{BWIM} decreases. Changes in A_{BWIM} due to structural deterioration are of similar magnitude regardless the profile. These results indicate that the proposed bridge monitoring method is not affected by the condition of the road profile significantly.

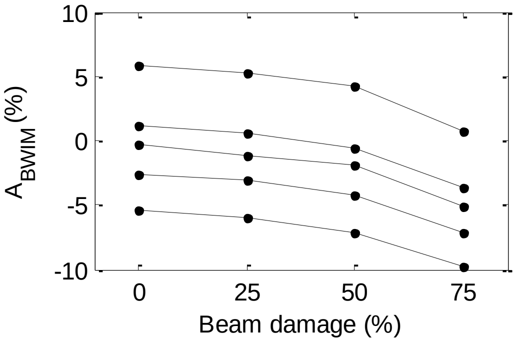

Fig. 7: Average A_{BWIM} for sensor and damage at ½ L

Next, the Monte Carlo results have been analysed in terms of average daily correlation parameter (A_{BWIM}). In this study one day of traffic consists of 1000 vehicles and the daily A_{BWIM} average is shown in Fig. 8. It presents the results for the three strain gauges for a bridge with increasing deterioration at ½ L section (i.e., 25%, 50% and 75% stiffness losses after 25, 50 and 75 days respectively). It is possible to observe the daily variations due to the random nature of the results.

But more importantly, it is evident how the average correlation parameter changes with structural damage.

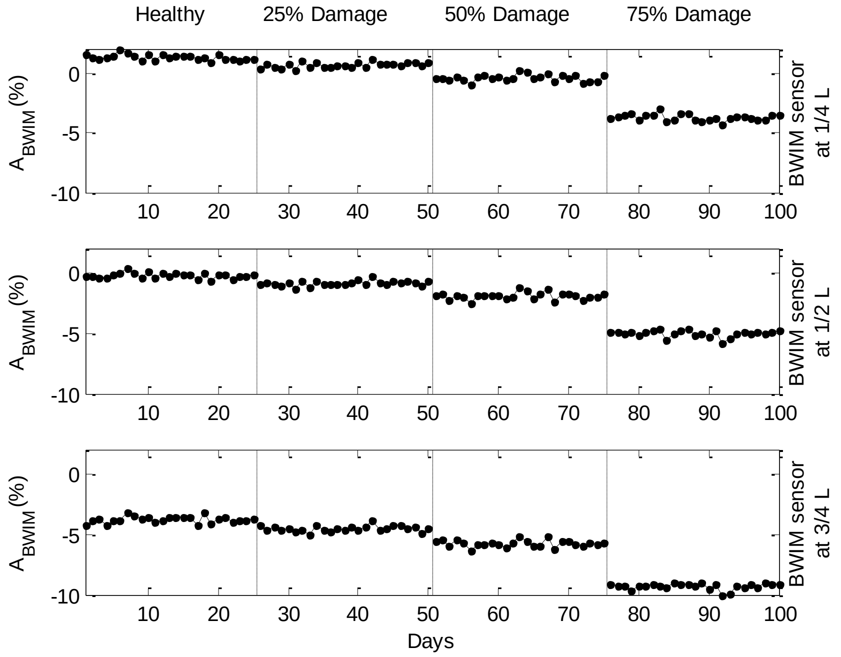

Fig. 8: Daily A_{BWIM} averages for damage at ½ L at three sensor locations

Fig. 9 presents the same analysis but for damage located at ¼ L. The results show significant variations due to damage only at the first sensor. This is in accordance with Fig. 4, since the sensitivity of damage in the remaining sensors is almost zerofor this particular case. Thus, a careful analysis of the variations inA_{BWIM} for each strain sensor could also provideinformation about the location of the damage.

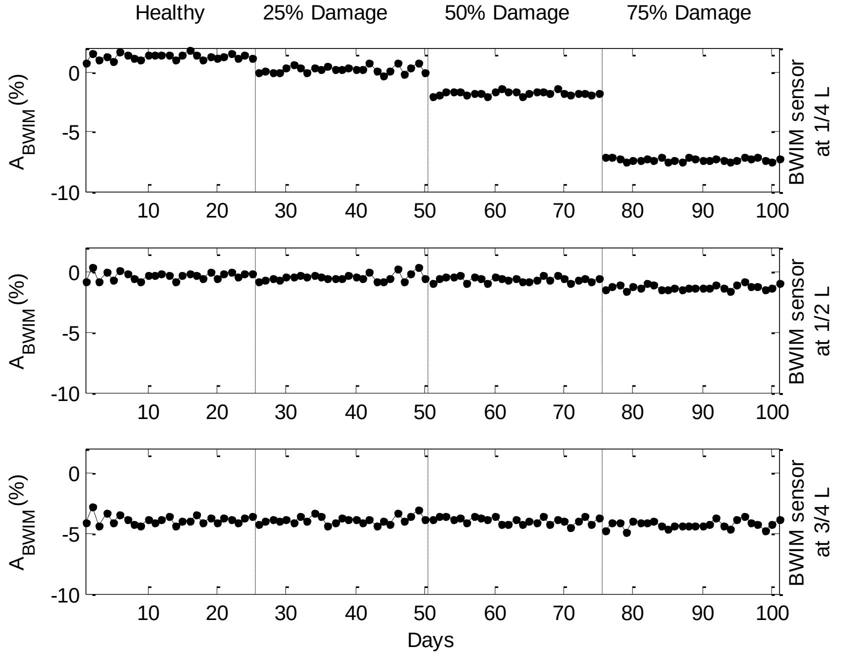

Fig. 9: Daily A_{BWIM} averages for damage at ¼ L at three sensor locations

Furthermore, the results in Fig. 8 and Fig. 9 feature greater variations than the changes expected in natural frequencies for the same damage (See Fig. 3). In particular, for 25% damage at ¼ L, the first natural frequency will decrease ≈0.1% whereas A_{BWIM}changes 1% approximately. In general the sensitivity of the proposed method is greater than a change in the frequency of the main mode of vibration of the bridge.

Conclusions

This paper has presented a novel bridge health monitoring method of short to medium span road bridges based on a combination of Weight-In-Motion and Bridge-Weigh-In-Motion systems.The approach has been numerically checked for various road profiles, damage and vehicle properties. The results indicate that localstiffness losses can readily be detected, being more sensitive to damagethan traditional monitoring methods based on frequency changes.

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