Drive-by methodologies for the condition assessment of railway bridges

Cássio Bragança[1] Edson Florentino de Souza[2,3], Túlio Nogueira Bittencourt[4], Diogo Ribeiro[5], Hermes Carvalho[6] Juliana Ferreira Fernandes[7]

[1] University of São Paulo (USP)/Department of Structural Engineering and Geotechnical/cassioscb@usp.br
[2] University of São Paulo (USP)/Department of Structural Engineering and Geotechnical/eflorentino@usp.br
[3] Federal University of Technology Paraná (UTFPR)/Department of Civil Engineering/eflorentino@utfpr.edu.br
[4] University of São Paulo (USP)/Department of Structural Engineering and Geotechnical/tbitten@usp.br
[5] Polytechnic of Porto/Institute of R&D in Structures and Construction (CONSTRUCT)/drr@isep.ipp.pt
[6] Federal University of Minas Gerais (UFMG)/Department of Structural Engineering/hermes@dees.ufmg.br
[7] University of São Paulo (USP)/Department of Structural Engineering and Geotechnical/julianaffernandes@alumini.usp.br

Abstract

Bridges are key elements of any transport infrastructure, avoiding the need for detours when crossing rivers and valleys. This aspect is even more important when it comes to the railway transport infrastructure since railway vehicles are not capable of overcoming very steep slopes. In recent times, the significant increase in speeds and axle load of trains were responsible for enhancing the dynamic actions imposed by the moving vehicles on the bridges. The increase in dynamic loads, associated with the aging of the railway infrastructure, reinforces the importance of having reliable and affordable methods for the early detection of bridge damage. In Brazil and around the world, the common practice is still performing periodic visual inspections, which typically are not capable of detecting premature damage. Although the installation of a dedicated Structural Health Monitoring (SHM) system allows for overcoming these limitations, the high cost of implementation restricts the application to the most critical bridges. To overcome this deficiency, methodologies capable of detecting bridge damage based on monitoring systems embedded in the vehicles, known as drive-by monitoring, have attracted the interest of researchers. Drive-by monitoring relies on the fact that the dynamic response of vehicles contains components associated with the bridges, through which modal parameters and damage-sensitive features can be extracted. Thus, a few instrumented vehicles can provide information about the state of several bridges, being a much more economical alternative. Given this context, this article presents a review of the current state of the art of drive-by railway bridge monitoring, covering theoretical, numerical, and experimental works and highlighting the difficulties to be overcome to enable commercial applications.

Keywords

Structural Health Monitoring; Drive-by Damage Detection; Indirect Monitoring, Railway Bridges

1. Introduction

Over the years rail transport has undergone several changes seeking to remain competitive in relation to other means of transport. These changes lead to a significant increase in speeds and the load per axle transported by the trains, which brings concerns about the safety of these vehicles running in an aging infrastructure that typically does not keep pace with the evolution of trains. Faced with this reality, it is increasingly necessary to monitor the structural integrity of critical elements of the railway infrastructure, such as bridges and viaducts, aiming at the early detection of damage and the orientation of repair actions (CARNEVALE; COLLINA; PEIRLINCK, 2019).

When it comes to bridge inspection, the current practice is to perform periodic checks by trained staff, which rely on visual techniques and the experience of the responsible technicians (MALEKJAFARIAN, A; MCGETRICK; OBRIEN, 2015). In the particular case of Brazil, guidelines for this type of inspection on reinforced concrete bridges and viaducts are defined in the ABNT NBR 9452 (2019) standard. Although it allows the detection of some types of anomalies, this traditional approach is time-consuming, costly, and can lead to subjective results (MALEKJAFARIAN, A; OBRIEN; GOLPAYEGANI, 2019; QUIRKE *et al.*, 2017). Due to these limitations, the application of Structural Health Monitoring (SHM) techniques has grown but, due to the high associated cost, they end up limited only to the largest and most important bridges (MALEKJAFARIAN, A; CORBALLY; GONG, 2022; MEIXEDO *et al.*, 2021).

Searching more economical alternatives, the development of drive-by methodologies has attracted great interest from researchers. The basic premise of the drive-by monitoring is the assessment of characteristics of the bridges through dynamic measurements carried out with measurement systems embedded in the vehicles during their normal circulation and, based on these data, monitoring the structural integrity of the bridge (Figure 1) (MALEKJAFARIAN, A; MCGETRICK; OBRIEN, 2015; YANG; YANG, 2018).

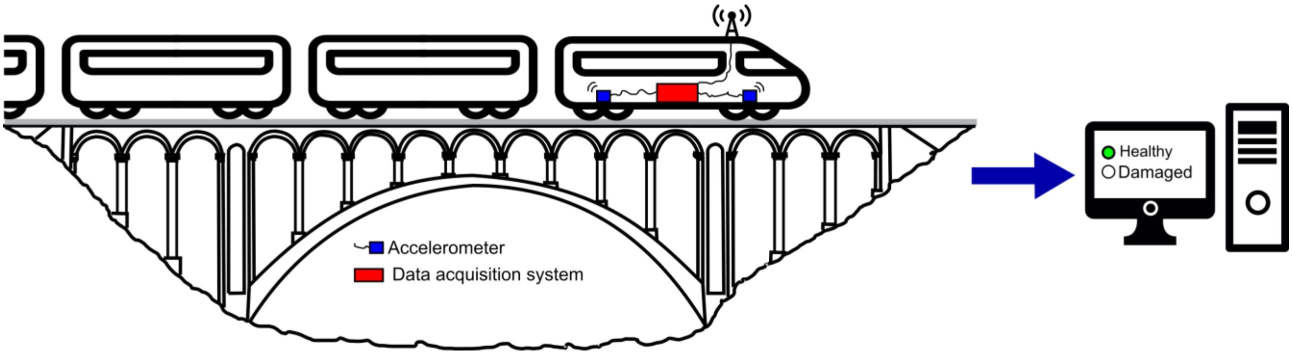


Figure 1 – Indirect bridge monitoring concept.

The possibility of extracting the dynamic properties of a bridge based on vehicle responses was initially raised in the analytical study conducted by Yang et al. (2004). The study involved a simplified model with a suspended mass and a double-supported beam representing, respectively, the vehicle and the bridge. These initial findings were further validated numerically by Yang & Lin (2005) and experimentally by Lin & Yang (2005a) in studies involving road bridges.

Since the introduction of the concept of drive-by monitoring, the possibility of inspecting the entire length of a railway with just one instrumented vehicle and making it economically viable to monitor small bridges and viaducts has attracted the interest of researchers to enable its practical application (LOCKE *et al.*, 2020). Initially, the drive-by methodologies as a whole were restricted to dedicated inspection vehicles at a very high cost, however, in recent years there has been a great effort by researchers to apply these techniques to common service vehicles (WARD *et al.*, 2011). For this purpose, it is necessary to develop advanced signal processing and damage identification tools, which must be robust enough to deal with adverse environmental and operational influences, such as: irregularities in the tracks, different vehicle speeds, temperature variations, winds, among others (MALEKJAFARIAN, A; CORBALLY; GONG, 2022).

Faced with this context, this work presents a review of the current state of the art involving the application of drive-by methodologies for monitoring the structural integrity of railway bridges. Firstly, a small theoretical background is presented. Then, works in the theoretical, numerical, and experimental scope are discussed in light of the challenges to be overcome to enable the practical application of these methodologies. Finally, a general overview of the works is made and future research trends in the area, according to the authors' opinions, are presented.

2. Theoretical introduction

When crossing a bridge, vehicle, and structure form a coupled dynamic system whose responses are closely linked to the physical properties of both. The presence of damage in a particular component of the bridge leads to a reduction in its stiffness and, consequently, a change in the bridge's dynamic response. The concept of indirect monitoring is based on the characterization of the dynamic response of a bridge, through measurements of the vehicle that travels over it and, based on changes in these responses, detect damage (MALEKJAFARIAN, A; CORBALLY; GONG, 2022).

Malekjafarian et al. (2015) present a didactic demonstration of the theoretical basis of indirect monitoring, initially introduced by Yang et al. (2004), based on the simplified ¼ vehicle model (Figure 2) in which the carbody and axle of the vehicle are simply represented by m_s and m_u, respectively.

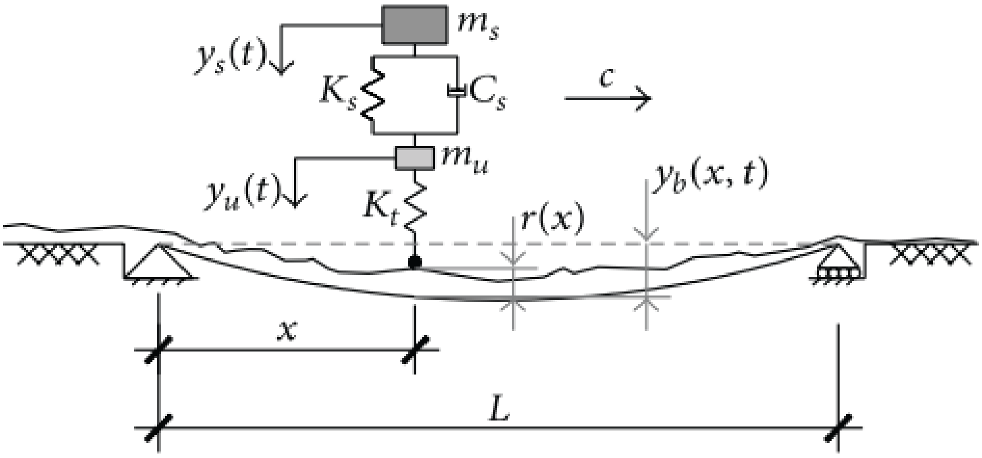


Figure 2 – Simplified model of the vehicle bridge interaction (MALEKJAFARIAN, Abdollah; MCGETRICK; OBRIEN, 2015)

The dynamic system of Figure 2 can be modeled by the following set of differential equations of motion:

$$\begin{aligned} m_s\ddot{y}_s + C_s(\dot{y}_s - \dot{y}_u) + K_s(y_s - y_u) = 0 \\ m_u\ddot{y}_u - C_s(\dot{y}_s - \dot{y}_u) - K_s(y_s - y_u) + K_t(y_u - y_b - r) = 0 \end{aligned} \tag{1}$$

where r and y_b represent, respectively, the profile of track irregularities and the displacement of the bridge under the vehicle. Given the presence of the y_b term in the system of coupled equations of motion, this simple example demonstrates that it is possible to obtain the dynamic response of a bridge based on displacements, velocities, and accelerations in different parts of the vehicle. Since in the presence of damage, the dynamic responses of the bridge will change, it is possible to identify this damage through dynamic measurement systems embedded in vehicles (MALEKJAFARIAN, A; MCGETRICK; OBRIEN, 2015).

In a practical application, however, as demonstrated by Meixedo et al. (2021) and Keenahan et al. (2020), typically, changes in the response of a bridge due to structural damage at an early stage are very small and can be easily masked by environmental actions such as temperature changes, winds, rain, among others. In addition, operational factors such as variations in train speed, load per wagon, and even the state of maintenance of vehicle suspensions can impact the results. Thus, extrapolating the simple example presented for practical applications involves overcoming several obstacles through the development of advanced damage detection methodologies.

3. Drive-by methodologies applied to railway bridges

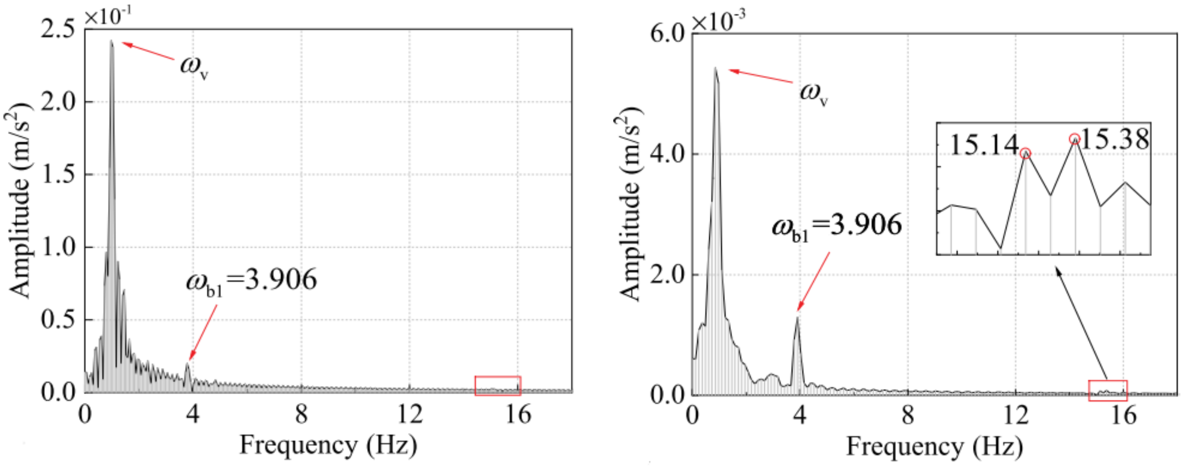
Although still in the early stages of research when it comes to railway applications, the number of works dedicated to the detection of damage based on railway vehicle responses has grown. The key to any vibration-based damage identification methodology is to extract damage-sensitive parameters from the dynamic responses, known as damage features (MEIXEDO et al., 2021). Historically, modal parameters such as natural frequency, damping ratio, and mode shapes have been the most used damage features within the SHM as a whole. However, in many cases, these are too sensitive to operational and environmental actions, mainly temperature variations. Aiming to overcome these issues, researchers have implemented other damage features through the application of techniques such as: Wavelet transforms, spectrograms, Fourier transform, apparent profile, Empirical Mode Decomposition (EMD) as well as artificial intelligence techniques for automatically identifying damage patterns in these indicators (MALEKJAFARIAN, A; CORBALLY; GONG, 2022).

In this section, some works involving the application of drive-by methodologies within the scope of railway bridges are reviewed. Firstly, studies involving modal properties assessment are reviewed, and then approaches based on damage assessment through other damage features are presented.

3.1. Modal based methodologies

After the foundations of drive-by monitoring being established in the aforementioned works (LIN; YANG, 2005b; YANG; LIN, 2005; YANG; LIN; YAU, 2004) researchers have concentrated efforts on solving the issues raised in these studies mainly related to track irregularities and vehicle speed. Corbally & Malekjafarian (2021) proposed a methodology for indirect damage detection based on variations of the first natural frequency of the bridge. The authors developed a formulation to infer the accelerations at the contact point and demonstrated that, as it is less affected by vehicle frequencies, it is more effective for characterizing the dynamics of the bridge. Then, the first natural frequency of the bridge was extracted from the acceleration spectrum calculated at the contact point. The method performed well in detecting variations in the natural frequency for low vehicle speeds, however, for higher speeds, contributions from track irregularities completely masked the responses of the bridge, preventing the identification of its natural frequency. Although they were not taken into account in this study, given the low sensitivity of the natural frequency to damage, temperature variations were identified as possible difficulties in possible practical applications.

In an attempt to improve performance under the influence of track irregularities, Zhan et al. (2021) studied the use of the Time-domain Subtraction Method (TSM) for the assessment of natural frequencies of a simply supported railway bridge. The TSM, proposed by Kong et al. (2017), consists in subtracting the acceleration response measured on the front and rear axles corresponding to the instant of time in which both axles are in the same position on the bridge. The idea behind the method is that since the axles are in the same position, they will be excited by the same irregularities but, because of the time lag, the contribution of bridge vibration will be different consequently the influence from irregularities is expected to be canceled out. The method was evaluated numerically for track Classes 1 (poor) to 6 (good) of the American standard and it was possible to verify that irregularities of Class 4 were already enough to make the identification of the natural frequencies of the bridge unfeasible without the application of TSM, as can be seen in Figure 3. Still within the scope of the study, parametric analyzes varying characteristics of the bridge and the vehicle and speed of circulation were carried out. Despite performing well under variations in most parameters, the increase in speed leads to a loss of accuracy in the method and at speeds of 20 m/s, errors of the order of 5% are already verified.

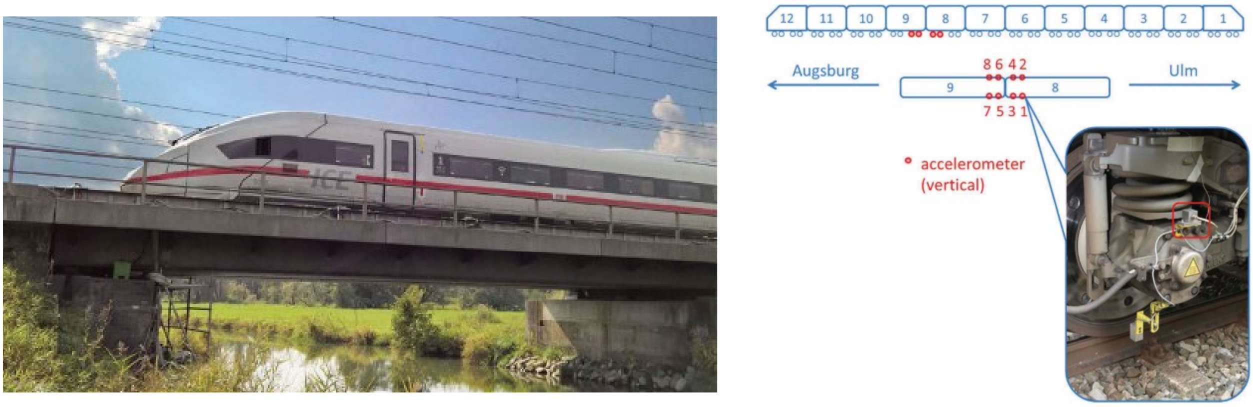


(a) (b)

Figure 3 – Acceleration spectra considering Class 4 irregularities (ω_v vehicle natural frequency and ω_b bridge frequency): (a) without TSM and (b) with TSM (ZHAN; WANG; *et al.*, 2021)

In a study specifically involving applications aimed at high-speed railway lines, Zhan et al. (2021) proposed the combination of the response of several consecutive wagons as a way to increase the amount of temporal information available for the calculation of the FFT. Furthermore, the effect of irregularities was minimized by using the response resulting from the subtraction between the accelerations of consecutive vehicles for the combination. The performance of the technique was investigated for different values of track irregularities, vehicle speeds, bridge stiffness, and damping as well as for the influence of measurement noise. The method proved to be extremely accurate in detecting the first natural frequency of the bridge even under the different values adopted in the parametric studies and at speeds of up to 360 km/h. Regarding the second natural frequency, this could also be identified although with a very reduced amplitude.

In addition to the purely numerical studies, although less widespread, recent experimental works focusing on the identification of natural frequencies of railway bridges can be found. Malekjafarian et al (2022) instrumented the bogies of a passenger train and collected vertical acceleration data during 41 passages of the train over the Malahide viaduct in Ireland, which is composed of 12 individual spans. The Hilbert Huang Transform (HHT) algorithm was used for the assessment of the natural frequency of each span. The results obtained by the drive-by methodology were compared to reference values, derived from instrumentation installed directly on the viaduct, and accurate results were achieved for all the spans except for the shorter ones at both ends of the viaduct. Lorenzen et al. (2022) used a large dataset composed respectively of 3,131 and 52 simulated and measured bogie vertical acceleration spectra to train a Neural Network (NN) to automatically identify the bridge's first natural frequency. The accuracy of the trained NN was tested for the Schmutter bridge (Figure 4a) using vertical acceleration data collected from a set of accelerometers installed on the bogie of an ICE4-type passenger train (Figure 4b). The model is very precise in assessing the first natural frequency and to be independent of vehicle velocity within the range of speeds evaluated (100 to 200 km/h). Besides that, the incorporation of measured data to train the NN has shown to be crucial to its accuracy.



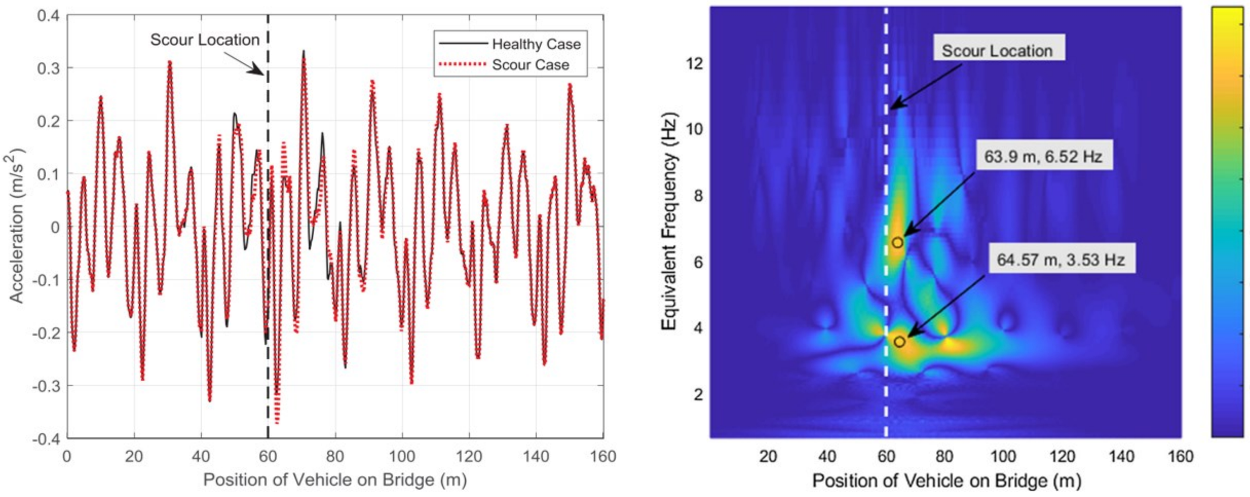
(a) (b)

Figure 4 – Natural frequency assessment of the Schmutter bridge: (a) bridge and ICE4 vehicle overview and (b) experimental setup (LORENZEN *et al.*, 2022).

Although it allows inferences about its existence, changes in the natural frequency do not provide information about the location of the damage, which led authors to be interested in the calculation of mode shapes. Yang et al. (2014) first introduced the assessment of the mode shapes from measured vehicle response during the crossing of a bridge which is excited only by the passage of the vehicle. A methodology capable of deriving several mode shapes from the Hilbert Transform of the bridge-related components in the vehicle response was proposed by these authors. Seeking to incorporate this important spatial information, OBrien & Malekjafarian (2016) proposed a methodology capable of identifying and locating damage to bridges based on a hypothetical vehicle instrumented with accelerometers and laser vibrometers. Through the absolute speed of the carbody, computed by integrating the acceleration, and the relative speed between the bridge and the carbody, measured by the vibrometers, the authors were able to calculate the speed of vibration of the bridge. Based on this, the modes were obtained by the Short Time Frequency Domain Decomposition (STFDD) technique proposed by Malekjafarian & OBrien (2014), which is based on the application of the Frequency Domain Decomposition (FDD) operational modal analysis technique to acceleration measured in consecutive axles. The identification and location of the damage was done using the indicator proposed by Zhang et al. (2012) defined as the difference between the square of the modal ordinates of the intact and damaged structure. The methodology was able to identify the presence of damage and, to a certain extent, indicate its position considering the influence of noise, irregularities, and speeds of up to 8 m/s. Other operational or environmental actions were not taken into account in the study.

3.2. Non-modal-based methodologies

Due to the aforementioned relatively low sensitivity to damage and being significantly affected by environmental influences researchers have sought other methodologies to locate damage instead of those based on modal parameters. Fitzgerald et al. (2019) studied the application of Continuous Wavelet Transform (CWT) in the detection of localized erosion in railway bridge pillars (scour) based on acceleration response at the bogies. The damage was modeled as a reduction of stiffness in the column and the bridge as a double-supported beam. The authors used the difference between the CWT coefficients for the intact and damaged bridge as a damage feature. As can be seen in Figure 5, the application of the CWT even reveals damage responsible for minor changes in accelerations (Figure 5a). To calculate these coefficients, the average of 200 train crossings was considered, in which the mass and speed of the vehicles were varied according to a normal distribution of probabilities, in addition to introducing noise into the data to simulate a real measurement environment. The results obtained indicated that the method performed very well in detecting and locating damage, even under simulated environmental and operational interferences. Based on the numerical models developed by Fitzgerald et al. (2019), Micu et al. (2022) modeled the train track interaction over the 12 spans of the Malahide viaduct in Ireland. Validation was performed by comparison with measured data demonstrating that the model can represent reasonably well the response of the bogies. Then, the validated model was used to evaluate the sensibility of bogie accelerations to damage on the spans, which leads to reductions in its stiffness, and scour, which leads to reductions in foundation stiffness. In this comparison, it was concluded that, although both are very discreet, scour damage results in more significant changes in the response. This finding is quite encouraging in terms of enabling the practical application of drive-by methodologies such as the one proposed by Fitzgerald et al. (2019) in detecting scour-type damage.



(a) (b)

Figure 5 – Bridge scour detection: (a) Bogie acceleration and (b) absolute differences between CWT coefficients. Adapted from (FITZGERALD *et al.*, 2019).

Quirke et al. (2017) applied the concept of apparent profile (AP) in the identification of damage in railway bridges. AP is a virtual longitudinal profile that, applied to the vehicle generates the same response as crossing the bridge. The authors generated a simulated dataset, based on a 3D numerical model of vehicle-structure interaction, for the intact and damaged bridge and added noise to represent a real measurement. The APs were generated, based on a 2D interaction model, through the minimization of an objective function composed by the quadratic sum of the errors in the acceleration signals in the bogies. Optimization was carried out by applying the cross-entropy (CE) heuristic methodology, which is based on the generation, by Monte Carlo simulations, of successive samples based on the statistical moments of the set formed by the best elements of the previous sample. The authors used variations in the area of the AP as an indicator of damage and were able to infer its location based on the peaks of the difference between the profiles of the damaged and intact bridge. Although not covered by this study, the authors highlighted the need to use calibrated models of vehicles to obtain the AP, as well as the need to investigate the influence of variations in temperature and mass of vehicles on the detection accuracy of the damage. In a very recent study, conducted by Ren et al. (2022), several issues for practical implementation of the methodology based on the AP were addressed. Firstly, a new method based on an Inverse Newmark-β integration scheme was proposed for calculating the AP, which is way more efficient and, consequently, more suitable for applications involving long bridges or even tracks with several small bridges. Besides that, properties like mass, moment of inertia, and train velocity will vary for each passage, and measuring them for every single train is unfeasible. To deal with this problem a self-calibration strategy, based on the CE optimization algorithm, was implemented forcing the AP calculated for several train passages to be the same. Regarding environmental effects, although their contribution was not evaluated, the use of an average response of several train passages is expected to wipe out its effects. Finally, a different damage feature was proposed based on the calculation, from the AP, of the moving reference influence line (MR-IL) of the bridge. The MR-IL, as expected, has shown to be very well correlated with bridge stiffness and therefore captured very well the stiffness reductions caused by damage.

In the works presented so far, the authors inferred the presence and location of the damage based on the direct interpretation of the features. Thinking about practical applications of this technology, such an approach may not be the most appropriate due to the large volume of data and the difficulty of distinguishing patterns associated with environmental interference from those related to damage, in addition to subjectivity in interpretation (LOCKE *et al.*, 2020; MALEKJAFARIAN, Abdollah; CORBALLY; GONG, 2022). With that in mind, some very recent works have studied the application of machine learning (ML) techniques to the detection of damage in railway bridges through vehicle responses. Hajializadeh (2022a) conducted a numerical study of the feasibility of using convolutional neural networks (CNN) to identify damage in railway bridges. The author used Bayesian Optimization to optimize the architecture of the pre-trained neural network GoogLeNet. The algorithm was supervised trained to recognize damage patterns from the CWT coefficients of the measured accelerations in the rail vehicle bogies. The algorithm performed quite well in identifying damage under different vehicle speeds, track irregularities, and the influence of measurement noise. Hajializadeh (2022b) used the same CNN for damage detection in a bridge miniaturized to scale based on the acceleration spectrograms measured in a train also miniaturized to scale (Figure 6). The author simulated the presence of damage by adding masses located at different locations on the model bridge. The algorithm performed quite satisfactorily in detecting different magnitudes of damage taking into account different vehicle speeds and since it is an experimental study real measurement noise is also present.

(a) (b)

Figure 6 – Scaled model: (a) Train and bridge overview and (b) sensor placement. Adapted from (HAJIALIZADEH, 2022b).

4. Conclusions

This article presents a review of works involving the application of drive-by methodologies in the condition assessment of railway bridges. First, a brief presentation of the theoretical bases of the problem that supported the first developments was made, as well as some pioneering works that introduced the method. Then, the issue of applying drive-by methodologies to railway bridges themselves was addressed. The works were divided into two groups composed of more traditional methodologies, based on the identification of modal properties, and methodologies based on other indicators. Throughout the review of the works, it can be seen that in theoretical terms and situations involving very simple models, the methodologies are already quite developed and robust. However, in the transition to practical applications, although some progress has been made by some authors proposing techniques capable of minimizing interference from irregularities, vehicle frequencies, environmental actions, and measurement noise, there is still a long way to go. A robust experimental basis, demonstrating the real effectiveness of these techniques in the day-to-day railway operations subject to all types of operational and environmental interference, is still needed to have confidence in drive-by methodologies.

Inevitably, practical uses will involve processing large volumes of information and a high ability to distinguish between various spurious interferences and the existence of damage itself. Therefore, in the authors' opinion, the future of these techniques lies in the development of methodologies associated with machine learning (ML) algorithms. The high capacity of these algorithms to extract patterns from large volumes of data, coupled with their ever-faster popularization and evolution, makes them ideal for this type of application. However, as can be seen throughout the article, studies involving ML applications linked to drive-by methodologies for condition assessment of railway bridges are still scarce, indicating the existence of a wide field for the development of new works.

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