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On the use of a passing vehicle for bridge health monitoring

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ABSTRACT: The large number of short-span and medium-span bridges in transportation systems makes it hard to instrument all of them for direct inspection. This issue has resulted in an increased interest in indirect monitoring of these bridges, i.e., monitoring using sensors in a vehicle passing overhead. With indirect monitoring, no sensors or data acquisition system needs to be installed on the bridge. This paper explains the theoretical background of indirect bridge monitoring and reviews the most important advances that have been made recently. Finally, there is discussion and recommendations on the most important challenges that remain.

1 INSTRUCTIONS

Improved condition monitoring of bridges is an important issue all over the world. The use of structural vibration data is one of the most popular Structural Health Monitoring (SHM) approaches for nondestructive damage assessment. The concept is that if damage occurs in a structure, it causes measurable changes in its dynamic properties. In most vibration-based bridge health monitoring techniques, sensors are installed on the structure to monitor the dynamic properties. These approaches, in which sensors are installed directly on the bridge, are referred to here as direct methods. The on-site instrumentation tends to be costly, time-consuming, and may even have safety implications, depending on the location and type of bridge.

Indirect approaches are referred to as those methods in which dynamic properties of bridge structures are inferred from the dynamic response of a passing vehicle. Such an approach is low cost and is aimed at reducing the need for any direct installation of sensing equipment on the bridge itself. The measured vehicle response needs to include relatively high levels of bridge dynamic response arising from vehicle-bridge interaction (VBI). In the case that only bridge frequency is required, the indirect approach has many advantages in comparison with direct methods in terms of equipment needed, specialist personnel on-site, economy, simplicity, efficiency, and mobility.

Over the past decade, many studies have been carried out on indirect bridge monitoring. This paper summarizes these approaches and provides recommendations for future development. It also helps readers in understanding and implementing the available bridge damage identification algorithms and signal processing methods based on the dynamic response of a moving vehicle.

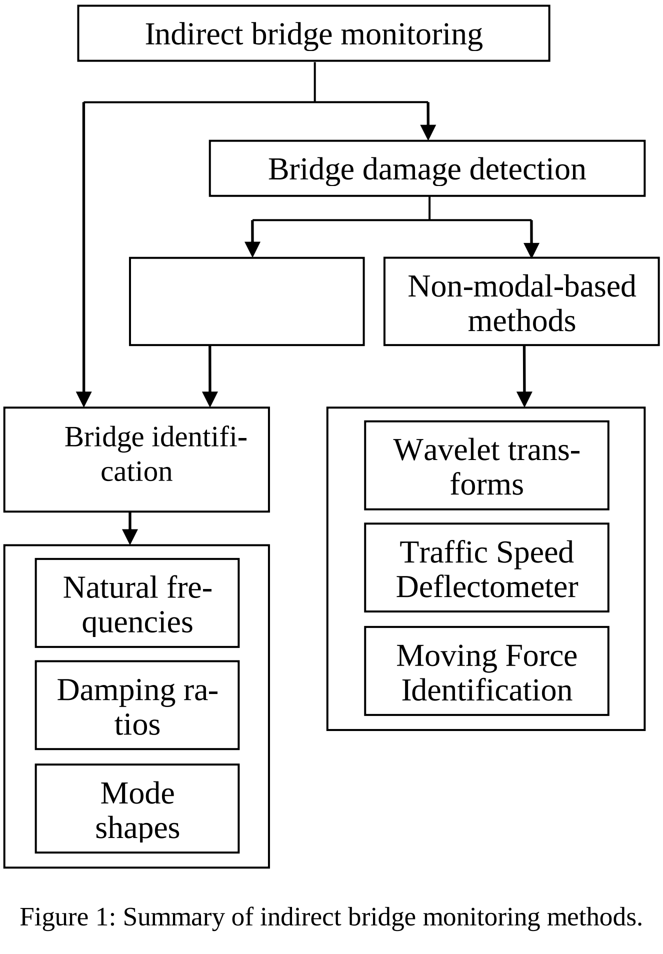


Figure 1: Summary of indirect bridge monitoring methods.

Generally indirect bridge monitoring methods can be divided into two main groups; bridge identification methods and bridge damage detection (Fig. 1). The main purpose of the first group is to identify the bridge modal parameters (natural frequencies, damping ratios and mode shapes). The second group exists of methods to detect bridge damage using the response measured on a passing vehicle. As shown in Fig. 1, the identified dynamic properties from the first group can also be used for damage detection purposes. Furthermore, some other methods have been proposed recently which are not based on the bridge modal parameters called non-modal based methods. All categories shown in Fig. 1 will be discussed in detail in following sections.

2 THEORETICAL RESPONSE OF A VEHICLE PASSING OVER A BRIDGE

If the vehicle is modelled as a sprung mass and the bridge is a simply supported beam considering only the first mode, the equation of motion for the sprung mass moving over the beam (shown in Fig. 2) can be written as (Yang et al., 2004):

$$m_v \ddot{q}_v + k_v \left(q_v - q_b |_{x=vt} \right) = 0 \tag{1}$$

where q_v is the vertical displacement of the sprung mass, m_v and k_v are the mass and stiffness of the sprung mass and $q_b |_{x=vt}$ is the beam deflection at the location of the sprung mass.

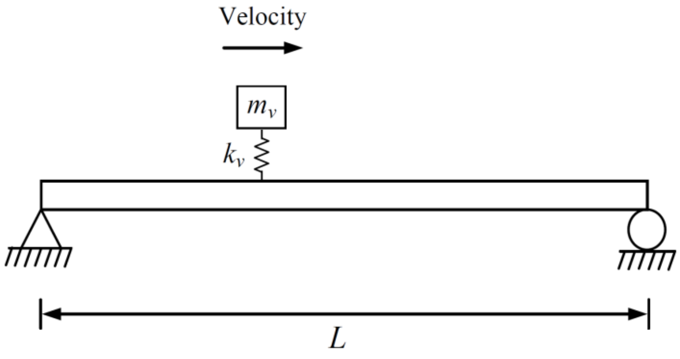


Figure 2: A sprung mass passing over a simply-supported beam.

By considering the contact force between the sprung mass and the beam and also the beam displacement due to a moving load, Eq. 1 can be expressed as (Yang et al., 2004):

$$m_v \ddot{q}_v + \left(\omega_v{}^2 m_v \right) q_v - \left[\omega_v{}^2 m_v \sin\left(\frac{\pi v t}{L} \right) \right] q_b = 0 \tag{2}$$

where ω_v is the vehicle natural frequency given by $\omega_v = \sqrt{k_v / m_v}$, v is the speed of the sprung mass, t is time and L is the total length of the beam.

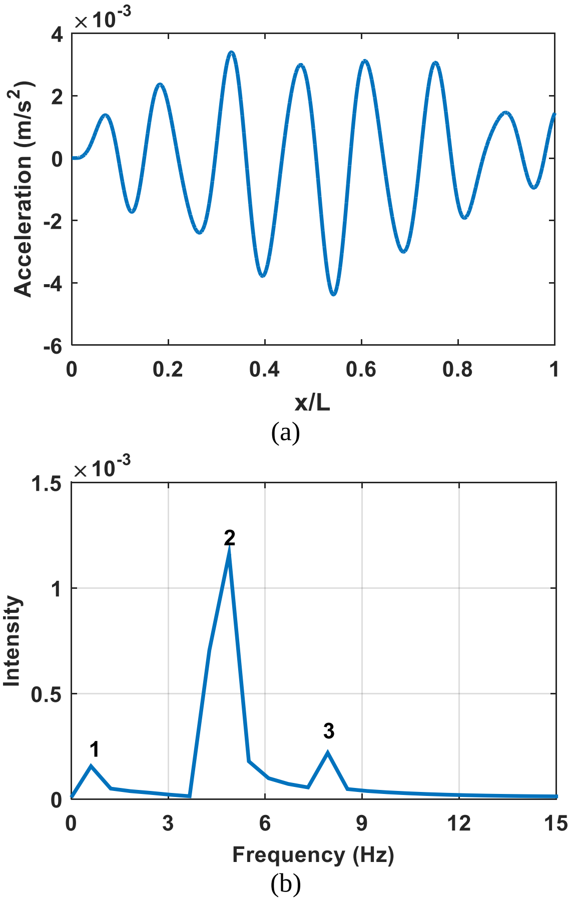
If the vehicle mass is much less than the total mass of the bridge, then the vehicle acceleration can be calculated from a closed-form approximation using (Yang et al., 2004):

$$\ddot{q}_v(t) = \frac{\Delta_{st} \omega_v{}^2}{2\left(1 - S^2\right)} \left[\begin{array}{l} \cos\omega_v t - \dfrac{(2\gamma S)^2 \cos 2\pi v t / L - \cos\omega_v t}{1 - (2\gamma S)^2} \\ - S \dfrac{\gamma^2 (1-S)^2 \cos\left(\omega_b - \pi v / L\right) t - \cos\omega_v t}{1 - \gamma^2 (1-S)^2} \\ + S \dfrac{\gamma^2 (1+S)^2 \cos\left(\omega_b + \pi v / L\right) t - \cos\omega_v t}{1 - \gamma^2 (1+S)^2} \end{array} \right] \tag{3}$$

where γ is the ratio of the bridge frequency to the vehicle frequency, $\mu = \omega_b / \omega_v$, Δ_{st} is approximately the static deflection at mid-span of the beam under the gravity action of the mass m_v at the same point (Yang et al., 2004). For a better understanding of the different components of the vehicle acceleration, Eq. 5 can be rewritten as:

$$\ddot{q}_v(t) = \frac{\Delta_{st} \omega_v{}^2}{2\left(1 - S^2\right)} \left[\begin{array}{l} A_1 \cos\omega_v t + A_2 \cos\dfrac{2\pi v}{L} \\ + A_3 \cos\left(\omega_b - \dfrac{\pi v}{L} \right) + A_4 \cos\left(\omega_b + \dfrac{\pi v}{L} \right) \end{array} \right] \tag{4}$$

where A_1, A_2, A_3 and A_4 determine the relative contributions of each component to the total acceleration response and can be found in (Yang et al., 2004).



(a)

(b)

Figure 3: Dynamic response measured on a passing vehicle; (a) acceleration, (b) FFT of the acceleration.

Eq. 4 shows that the vehicle response is dominated by three main frequencies; the vehicle frequency, driving pseudo frequency of the moving vehicle and two shifted frequencies of the bridge. Such a response is shown for a simple case study of a sprung mass system (m = 700 kg and k = 1.75×10^6 N/m^2) passing over a bridge in Fig. 3 (a). The bridge properties are given in Table 1.

Table 1. Properties of the bridge.

Properties	Unit	Symbol	value
Length	m	L	15
Mass per unit length	kg/m	m	28125
Modulus of elasticity	N/mm^2	E	35000
Second moment of area	m^4	J	0.5273
First natural frequency	Hz		5.65

The Fast Fourier Transform of the acceleration is shown in Fig. 3(b) where the three peaks corresponding to; (1) driving frequency, (2) the bridge natural frequency and (3) the vehicle frequency, are shown. A detailed investigation of the main components is useful to understand the potential of such a response for bridge monitoring. The main components are plotted separately in Fig. 4.

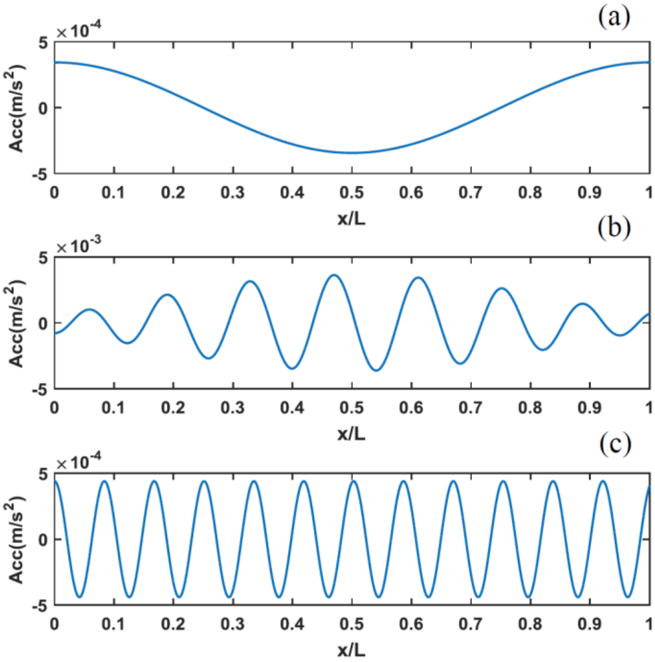


Figure 4: The main components of the vehicle response; (a) driving frequency, (b) the bridge natural frequency and (c) the vehicle frequency.

The first two components in this figure correspond to the bridge vibration. As shown in Eq. 2, these components arise in the equation of motion from excitations applied from bridge displacement to the sprung mass. As a smooth road profile is considered in this example, the sprung mass oscillates at its natural frequency and the excitation frequencies (including the driving frequency and the bridge natural frequency). This is the basis of most indirect methods. The indirect bridge frequency monitoring methods rely on the second part where the bridge natural frequency can be detected. But the most important challenge for all of them is when road profile roughness is considered in the simulation. Then, the road surface can apply a range of frequencies as excitation to the sprung mass. In most cases, the bridge vibration is not dominant in the excitation of the mass sprung system. Therefore, the bridge vibration plays a small part in the total response of the axle. This can be a bigger problem when the vehicle speed is high, where few cycles of the bridge response can be measured in the vehicle response. A similar explanation can be presented for identification of bridge mode shapes from this response. It is shown in Yang et al. (2014) that the instantaneous amplitude of this response at bridge natural frequencies can reveal the corresponding bridge mode shape. It means that this part of the vehicle response includes the bridge mode shapes information in addition to the bridge natural frequencies.

The presence of a crack on the bridge causes a global change in the bridge natural frequency and a local change in the bridge mode shape. Therefore, the second component of the vehicle response can be used for damage detection by detecting a change in natural frequency and also damage localization using a change in the bridge mode shape (OBrien and Malekjafarian, 2015b).

It is suggested in He and Zhu (2015) that the moving frequency component of the bridge response to a moving load is very sensitive to damage and can be used for damage localization. It means that when a vehicle passes over the damaged section of the bridge, a discontinuity can be observed in this component. Such a discontinuity can be detected in the first component of the vehicle frequency shown in Fig. 4. However, it should be considered that the level of this component is very low compared to the total response which makes it difficult to detect it in the total response.

3 INDIRECT BRIDGE IDENTIFICATION

Identification of bridge dynamic properties such as natural frequencies and mode shapes plays an important role in bridge monitoring. Most of the vibration-based structural health monitoring methods are based on these properties. The most important methods of indirect identification of bridge dynamic properties are reviewed in this section.

3.1 *Bridge natural frequency*

The extraction of bridge frequencies from the dynamic response of a passing vehicle is first suggested by Yang et al. (2004) in a theoretical study.

Further investigations are carried out by Yang and Lin (2005) to confirm the feasibility of the bridge frequency extraction idea. Following this study, a considerable volume of literature has been published on efficient identification of bridge natural frequencies from indirect measurements through numerical and experimental studies.

3.1.1 *Numerical examples*

In order to have a more successful extraction of the bridge frequencies Yang and Chang (2009a) perform a parametric study showing that the magnitude of the shifted bridge frequency peaks in the vehicle response relative to that of the vehicle frequency peak, are important for successful bridge frequency extraction. It is suggested that the most important variable is the initial vehicle/bridge acceleration amplitude ratio; the smaller this ratio, the higher the probability of successful bridge frequency extraction.

In addition to the bridge first natural frequency, the higher modes are identified by adopting the empirical mode decomposition (EMD) technique for pre-processing of vehicle measurements by Yang and Chang (2009b). The first few frequencies of the bridge are extracted in a numerical study and the second natural frequency is detected in a full scale experimental case study.

Li et al. (2014) develop a new theoretical approach based on an optimization method applied to the responses of a simplified vehicle-bridge interaction system with a smooth road profile surface. The bridge frequency and stiffness are identified with reasonable accuracy.

A well-known output-only modal analysis method called Frequency Domain Decomposition (FDD) has been applied to the vehicle signal in a theoretical investigation (Malekjafarian and OBrien, 2014a). It is shown that the FDD method is effective for the case of close bridge and vehicle frequencies in the presence of a road profile. The authors show that the FDD method can identify both bridge and vehicle frequencies in this case.

In a real VBI system, the frequencies of the bridge and/or vehicle may vary during the interaction between them. Yang et al. (2013c) investigate how the instantaneous frequencies of bridges vary under moving vehicles using a theoretical framework. It is stated that the frequency variation caused by the moving vehicle should not be neglected, particularly for the case where the vehicle mass is not negligible compared with the bridge mass.

The road profile can have a negative effect as the vehicle frequencies will usually appear as dominant peaks in the spectrum of the vehicle response and this makes it difficult to detect the bridge frequency peak (Siringoringo and Fujin, 2012) . Yang et al. (2013a) utilize some filtering techniques to filter the vehicle frequency from the spectrum. It is demonstrated that the vehicle frequencies can be filtered out from the spectrum and this helps the visibility of the bridge frequency.

The Stochastic Subspace Identification (SSI) method which is a time domain output-only modal method, is modified in Yang and Chen (2015) to express the vehicle and bridge in state space. It is shown in the numerical case study that the vehicle frequency can be suppressed which is helpful to make the bridge frequency more visible.

3.1.2 *Experimental cases*

An experiential case study conducted by Lin and Yang (2005) is one of the earliest efforts at validating the idea of indirect bridge monitoring in a real field test. A tractor-trailer is used to pass over a 30 m span prestressed concrete bridge in Taiwan. They mention that lower vehicle speeds (less than 40 km/h, or 11.1 m/s) provide the best results. The existence of ongoing traffic is suggested to be useful as it adds to the excitation of the bridge. Oshima et al. (2008) suggest using a heavy vehicle equipped with an excitation machine to apply a constant vibration to the bridge in a field experiment.

The feasibility of a drive-by frequency inspection approach is presented by Kim et al. (2011) and Toshinami et al. (2010) in scaled laboratory experiments. The authors show that higher vehicle speeds provide larger magnitude frequency peaks in the spectra of the vehicle response.

An idea of using a specialized vehicle is suggested by Yang et al. (2013b). A hand-drawn test ‘cart’ (trailer) is introduced in an experiment to control the negative effects of VBI. The authors adjust the dynamic characteristics of the test cart for successful extraction of the frequencies of the bridge.

Nagayama et al. (2015) propose a new approach using two different vehicles moving across the bridge. The common vibration component of the acceleration responses measured on the vehicles is obtained using their individual power spectra and cross-spectrum. It is shown in a numerical study that the method is feasible for a relatively low driving speed. A similar result is obtained from the field measurement, confirming the practicality of the strategy. The estimated bridge natural frequency is found to be in fair agreement to the values obtained from direct measurement, with the largest discrepancy being just 3.20%.

3.2 *Bridge damping*

Several attempts have been made to estimate bridge damping using an instrumented vehicle. McGetrick et al. (2009) show that the magnitude of PSD in the spectra of vehicle accelerations, at both bridge and vehicle frequency peaks, decreases with increased bridge damping. The results are confirmed in scaled laboratory experiments for repeated bridge crossings and three vehicle speeds (McGetrick et al., 2010, Kim et al., 2014).

Gonzalez et al. (2012) propose a new six-step algorithm for the identification of damping in a bridge using a moving instrumented vehicle. The bridge damping is identified with reasonable accuracy using an iterative procedure in theoretical simulations. In the parametric study, the method is found to be relatively insensitive to road profile, low levels of measurement noise and modelling errors. In particular, this method overcomes the effect of road profile highlighted in previous studies as the six-step algorithm actually estimates the road profile under each vehicle wheel.

3.3 *Bridge mode shapes*

Recently, researchers have shown an increased interest in the identification of bridge mode shapes from indirect measurements. Yang et al. (2014) explain theoretically how the dynamic response of a vehicle contains the bridge mode shape information. As the vehicle can be considered as a moving sensor, the bridge response can be collected from all points of the bridge at the vehicle location. It is demonstrated that the bridge component of the response measured on a passing vehicle oscillates at each bridge natural frequency with varying amplitude that is identical to the corresponding bridge mode shape. The bridge mode shapes are obtained from the instantaneous amplitude history of the vehicle response using the Hilbert transform. It is demonstrated that the method can detect mode shapes of lower modes accurately while accuracy reduces for higher vehicle speeds tested. The road surface profile causes a significant reduction in accuracy.

Oshima et al. (2014) propose a truck-trailer configuration for the identification of bridge mode shapes. Singular Value Decomposition (SVD) is used in a four-step process. Accelerations of the monitoring vehicles and the relative displacement between the axle mass and the road surface are measured.

A new method called Short Time Frequency Domain Decomposition (STFDD) is proposed in (Malekjafarian and Obrien, 2014b, OBrien and Malekjafarian, 2015a) for indirect identification of bridge mode shapes using responses measured from two following axles passing over a bridge. They apply the FDD method to the short time measured signals obtained at several defined stages and perform a rescaling procedure on local mode shape vectors to obtain the global mode shapes (Fig. 5). The effect of road profile in exciting the vehicle is a significant challenge for the method. If noise is sufficiently low and the vehicle speed is 2 m/s or less, mode shapes can be found with reasonable accuracy. In addition, it is found in this study that applying ongoing traffic can reduce the sensitivity of the method to noise.

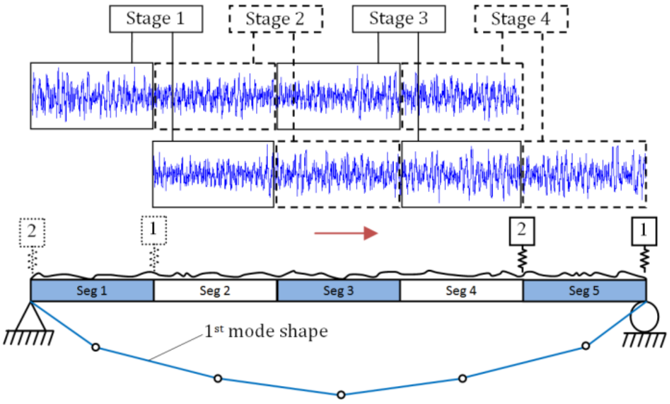


Figure 5: Summary of the STFDD method.

3.4 *Indirect bridge damage detection*

As shown in Fig. 1, many methods have been proposed recently which they are not based on identification of bridge modal parameters. These methods usually take advantage of other ideas to detect damage on the bridge. McGetrick (McGetrick, 2012) suggests using the idea of Moving Force Identification in which the time history of forces applied to the bridge can be estimated. It is shown that the calculated pattern of applied force is sensitive to bridge damage. In addition, the authors present the possibility of identification of the global bending stiffness of the bridge.

The concept of modal strain energy and the Genetic Algorithm (GA) is employed in (Li and Au, 2014) in a multi-stage damage detection method. It is shown that the approach can successfully identify the damage location in a numerical case study. The authors also compare the proposed approach with wavelet-based and frequency-based damage detection methods (Li and Au, 2015) to show its ability in the presence of a road profile.

McGetrick and Kim (2013), (McGetrick and Kim, 2014) suggest using a Continuous Wavelet Transform (CWT) to the dynamic response of a vehicle passing over a bridge. The idea is that when the axle passes over a damaged section, the damage can be identified and located using the CWT coefficients. The performance of the method is confirmed through theoretical and experimental case studies.

The idea of using a Traffic Speed Deflectometer (TSD) for indirect bridge damage detection is first introduced in a numerical study in (Keenahan and OBrien, 2014). A TSD model with three displacement sensors is proposed which removes the bounce motion of the vehicle and the road profile influence. The authors also introduce the concept of ‘apparent profile’ in (OBrien and Keenahan, 2014). They go on to show that this apparent profile is quite sensitive to bridge damage.

4 DISCUSSION

As mentioned in Section 2, most of the reviewed methods in this paper can be explained based on the main component of the vehicle response. The methods discussed in sections 3.1 and 3.2 detect the bridge natural frequencies and damping ratios from the second component while they are trying to overcome the challenge of a road surface profile in the response (Keenahan et al., 2014, Yang et al., 2012).

In most of the studies considered, the vehicle speed is assumed to be constant. In practice, it may not be easy to maintain this during the vehicle crossing. This factor becomes more significant when the signals of two axles are subtracted to minimize the influence of road profile. Therefore, speed variation should be investigated in future studies.

On the other hand, temperature/environment can have a significant effect on most damage indicators and this influence is difficult to distinguish from real damage. This can be addressed by instrumenting vehicles that travel on the same route frequently as this allows environmental effects to be averaged out (Malekjafarian et al., 2015).

In summary, the main challenges for indirect bridge monitoring methods are:

- The road profiles.
- The limited VBI time.
- Environmental effects.

Although the concept of subtracting signals from identical axles requires very high measurement accuracy, it has made good progress in addressing the influence of the road profile. The speed of the vehicle means that it is only present on the bridge for a limited time which results in an inevitable shortage of vehicle-bridge interaction measurement data. Some studies require that speeds are very slow to address this problem but this is not ideal on busy roads where congestion may result. The final challenge in indirect monitoring is interference from environmental effects such as temperature. The most promising approach to tackle this issue is indirect monitoring using vehicles that repeatedly pass over the bridge. The potential of indirect methods is well illustrated in the literature, as discussed in this paper. Therefore, overcoming these challenges would represent a big step towards successful implementation of indirect bridge monitoring methods in practice.

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