ABSTRACT: Bridges are critical elements in any road or rail transport network and ensuring their safety is paramount. Recent years have seen significant research efforts to develop cost-effective techniques for bridge monitoring on a large scale. Drive-by bridge inspection techniques, whereby sensors inside a vehicle are used to monitor bridge condition, are at the focus of much of this work. This paper develops a relationship between the measured response in a vehicle and the contact-point response between the wheel and the surface of a bridge using a quarter-car representation of the vehicle. Numerical simulations are carried out to examine the feasibility of using the contact-point response as an indicator of damage. A number of passages of the quarter-car vehicle model traversing a Finite Element representation of a bridge are simulated and the contact-point response is evaluated for each passage. Varying levels of damage are simulated in the bridge to assess whether the presence of damage can be detected by the contact-point response. Results show that the method is very effective at identifying the bridge frequencies and can also detect changes in bridge frequency with increasing damage levels. A major advantage of using the contact-point response as a damage indicator lies in its ability to detect bridge frequencies without being influenced by the vibrational frequencies of the vehicle itself. The contact-point response shows promise for implementation into drive-by bridge inspection regimes, however further work is required to investigate the feasibility of the approach at higher vehicle speeds.

KEY WORDS: Drive-By; Bridge; Structural Health Monitoring; SHM; Damage Detection; Contact-Point Response.

1 INTRODUCTION
The efficient functioning of any country’s economy relies heavily on a good quality transport infrastructure. With road and rail being prominent modes of transport for both goods and people, it is imperative that the physical condition road and rail infrastructure can be monitored. Ongoing monitoring allows repairs and maintenance to be proactively carried out in order to avoid disruptions on the network.

Bridge failures can have catastrophic effects, not only in relation to fatalities or damage associated directly with the collapse, but also to the functioning of the transport network in the aftermath. Concerns regarding the safety of bridges are becoming more and more prominent following a number of high-profile bridge collapses in recent years. In April 2020, the 260m long Capigliola Bridge, a 5-span concrete structure in Italy, suffered a complete collapse. The consequences were luckily limited due to travel restrictions which were in place at the time during the COVID-19 pandemic, meaning that the bridge collapse resulted in only minor injuries to two truck drivers. Other bridge collapses in recent years have had more significant consequences. In 2018, the collapse of the Ponte Morandi viaduct in Genoa, Italy, resulted in 43 deaths and a state of emergency in the Liguria region.

Limited maintenance budgets, coupled with an ageing bridge-stock, mean that there is much appetite for efficient and inexpensive techniques for monitoring and detection of damage in bridges. With the world’s bridge-stock ageing and deteriorating over time, it is essential that measures can be put in place to monitor these structures and identify damage or deterioration to provide advance warning to infrastructure owners so that repairs or preventative maintenance can be targeted towards structures which may be at risk of failure.

Structural Health Monitoring of bridges is becoming more commonplace, particularly for larger structures on major transport routes, whose closure would result in significant disruption to transport and cause major financial losses to the economy [1]. These SHM strategies often require customised designs for sensor installations which are bespoke to the individual structure being monitored. The installation of sensors on individual bridges is expensive and time consuming and is not feasible for large-scale monitoring of all bridges on the transport network. In response to this problem, research efforts have focused on various approaches to facilitate large-scale monitoring of the condition of bridges on the transport network. The concept of using sensors located within vehicles, using a drive-by approach to monitor the condition of bridges, has become the focus of much attention in recent years.

The drive-by concept was initially proposed by Yang et al. [2] in 2004 and since then, there have been significant developments in the area of drive-by bridge inspections. The majority of drive-by approaches make use of the fact that the vibration characteristics of a bridge are likely to change when the structure becomes damaged or has deteriorated over time [3]. Different damage mechanisms can affect bridge vibrations in different ways so there have been various efforts to examine how drive-by techniques can be used to identify these changes, e.g. for scour [4], cracking in the deck [5, 6] or changes in boundary conditions [7, 8] amongst others. Drive-by techniques have also been used for different applications, including calculation of bridge damping [9], estimation of vehicle properties and investigation of pavement characteristics [10, 11].
The drive-by approach has demonstrated the ability to extract the fundamental frequency of vibration of the bridge, based solely on measurements taken within a vehicle [12, 13]. As such, most drive-by approaches aim to monitor the natural frequency of the bridge over time to identify any changes which may be indicative of damage to the bridge. One of the primary difficulties faced when using this approach relates to the separation of bridge-related frequencies from the vehicle frequencies in the measured response. The vehicle frequencies are often shown dominate the overall response [14] and can mask the contribution of bridge vibrations to the vibrations measured within the vehicle.

Yang et al. [15] developed a formulation which allowed the response of the point of contact between the vehicle and the bridge to be derived from the measured response within the vehicle. The formulation was developed for a single degree of freedom, sprung mass, model. This model was used to represent a specific trailer which was designed to be towed across a bridge. The contact-point response calculated from the measurements within the vehicle was then used to detect the bridge frequencies. Results from field testing of the approach were promising and demonstrated the ability to extract the bridge frequencies with little interference from the vehicle frequencies.

In order to extend the approach to more commonly used vehicles, the vehicle suspension and vibration of the vehicle body need to be considered. This paper develops a relationship between the measured accelerations within a quarter-car representation of a vehicle and the response at the contact-point with the bridge. The contact-point response derived in this paper is shown to be capable of accurately identifying the bridge frequencies, and also the change in these frequencies as increasing levels of bridge damage are simulated.

2 NUMERICAL MODELLING APPROACH

2.1 Vehicle-Bridge Interaction Modelling

Numerical simulations are used in this paper to examine the potential for using the contact-point response to identify the natural frequencies of a bridge and to investigate whether changes to the natural frequency, due to damage, could be identified.

The simulations were carried out using a Finite Element (FE) beam model representing a 15m long simply supported concrete slab bridge as presented by Malekjafarian et al. [16]. The properties of the bridge are listed in Table 1. The FE model consisted of 20 no. beam elements, 0.75m long, with 2-degrees of freedom per node, representing rotational and vertical displacements.

![Figure 1. Vehicle-Bridge Interaction Model](image)

### Table 1. Properties of FE Beam Model

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (L)</td>
<td>15 m</td>
</tr>
<tr>
<td>Young’s Modulus (E)</td>
<td>35 GPa</td>
</tr>
<tr>
<td>Cross Sectional Area (A)</td>
<td>7.5 m²</td>
</tr>
<tr>
<td>Second Moment of Area (I)</td>
<td>0.352 m⁴</td>
</tr>
<tr>
<td>Material Density (ρ)</td>
<td>2,500 kg/m³</td>
</tr>
</tbody>
</table>

In order to consider the interaction between the vehicle and the bridge, a quarter-car model was used to represent the vibration of the vehicle. The quarter car model, as shown in Figure 1 & Figure 5, consists of two degrees of freedom, with two lumped masses, representing the vertical motion of the (i) vehicle body and (ii) the axle (including the wheel). The two masses are connected using a spring and dashpot representing the stiffness and damping properties of the vehicle suspension and the axle degree of freedom is connected to the bridge using a spring to represent the tyre stiffness. While the quarter-car is a simplified representation of the actual behaviour of a vehicle, it has been widely adopted to represent the two primary modes of vibration of a vehicle, i.e. ‘bounce’ of the vehicle body and axle ‘hop’ [17]. The properties used in the quarter-car model and the natural frequencies of the model are included in Table 2.

### Table 2. Properties of Vehicle Model

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body Mass (M&lt;sub&gt;b&lt;/sub&gt;)</td>
<td>9,300 kg</td>
</tr>
<tr>
<td>Axle Mass (M&lt;sub&gt;axl&lt;/sub&gt;)</td>
<td>700 kg</td>
</tr>
<tr>
<td>Suspension Stiffness (k&lt;sub&gt;s&lt;/sub&gt;)</td>
<td>4x10⁴ N/m</td>
</tr>
<tr>
<td>Suspension Damping (c&lt;sub&gt;s&lt;/sub&gt;)</td>
<td>10,000 Ns/m</td>
</tr>
<tr>
<td>Tyre Stiffness (k&lt;sub&gt;t&lt;/sub&gt;)</td>
<td>17.5 x10⁵ N/m</td>
</tr>
<tr>
<td>First Frequency (body bounce)</td>
<td>0.9 Hz</td>
</tr>
<tr>
<td>Second Frequency (axle-hop)</td>
<td>8.8 Hz</td>
</tr>
</tbody>
</table>

The analysis involved simulating the passage of the quarter-car over the bridge at a constant speed and finding the dynamic response of the vehicle and the bridge. Bridge damping was not considered within the model and a sampling frequency of 2000 Hz was used in the simulations.

The acceleration response of the quarter-car model was then used to represent measured response from the vehicle axle or within the vehicle itself. These measurements could be used as inputs to the drive-by algorithm to try and identify the natural frequencies of the bridge.
Figure 2 shows the simulated acceleration response from the quarter car when it passes over the bridge at a speed of 5 m/s. The bridge is considered to have a perfectly smooth surface (i.e. with no pavement roughness included in the simulation). Figure 3 shows the Fast Fourier Transform (FFT) of the axle response, which is used to evaluate the frequency content of the signal. It can be seen that the first two bridge frequencies can clearly be identified from the vehicle response.

2.2 Simulation of Damage

Damage due to cracking was numerically simulated in the beam model. Damage was considered as a loss of stiffness in the region of the crack. The loss off stiffness was also considered to propagate outwards from the location of the crack to a distance of 1.5 times the depth of the crack, either side of the crack location. In order to include this damage representation within the FE model, the elements within the zone of influence of the crack were reduced in stiffness. The adjusted ‘I’ values for each element within the zone of influence were calculated assuming a linear change in stiffness from the location of the crack to the edge of the zone of influence, as summarised in Figure 4. Figure 4 shows a crack of depth ‘δ’ at the mid-span of the beam of depth ‘h’ and width ‘b’. The image shows the finite element mesh and highlights the elements of reduced stiffness in the region of the crack.

3 CONTACT-POINT RESPONSE FORMULATION

In order to extend the approach proposed by Yang et al. [15] to more commonly used vehicles, the vehicle suspension and vibration of the vehicle body need to be considered. In this paper a quarter-car model is used to consider these effects. Figure 5 shows the quarter-car model used in the analysis, where \( y_v \) and \( y_w \) represent the displacement of the vehicle body and the wheel/axle respectively and \( u_{cp} \) represents the deflection at the contact point between the wheel and the surface of the bridge. The remainder of the vehicle properties are as described in Table 2.

Equation 1 shows the formulation of the equations of motion for the quarter-car model shown in Figure 5, with dot notation used to indicate the time derivatives of variables (i.e. velocity and acceleration). The symbols are as defined in the previous paragraph and in Table 2.

\[
\begin{bmatrix}
M_v & 0 \\
0 & M_w
\end{bmatrix}
\begin{bmatrix}
\ddot{y}_v \\
\ddot{y}_w
\end{bmatrix}
+ \begin{bmatrix}
c_v & -c_v \\
c_v & c_v
\end{bmatrix}
\begin{bmatrix}
\dot{y}_v \\
\dot{y}_w
\end{bmatrix}
+ \begin{bmatrix}
k_v & -k_v \\
-k_v & k_v + k_T
\end{bmatrix}
\begin{bmatrix}
y_v \\
y_w
\end{bmatrix} = \begin{bmatrix}
0 \\
k_T u_{cp}
\end{bmatrix}
\]  

(1)

Utilising the axle/wheel equation from Equation 1 and rearranging in terms of the contact-point acceleration, \( u_{cp} \), the contact-point response can be represented by the formulation shown in Equation 2:
\[
\ddot{u}_{cp} = \frac{1}{\omega^2} \frac{d^2 \ddot{y}_v}{dt^2} + \frac{cv}{k_T} \left( \frac{d \dot{y}_W}{dt} - \frac{d \ddot{y}_v}{dt} \right) \\
+ \frac{k_v}{k_T} (\ddot{y}_W - \ddot{y}_v) + \ddot{y}_W
\]  
(2)

Where \( \omega = \sqrt{\frac{k_T}{M_w}} \) is the axle-hop frequency of the vehicle model and the \( \frac{d^n \ddot{y}_v}{dt^n} \) notation is used to represent the \( n \)th time derivative of the measured acceleration signals from the vehicle. All other parameters are as defined above and in Table 2.

This relationship between the measured accelerations in the vehicle, and the acceleration at the contact point, can be used to infer the contact-point response directly from measurements within the vehicle, once the properties of the vehicle are known.

Figure 6 shows the contact-point response and the axle response from the vehicle model generated during a 5m/s passage of the vehicle across the bridge, with a perfectly smooth surface. It can be seen that the contact-point response largely captures the same frequency components as the axle response, however there are also higher frequencies present in the signal.

4 RESULTS

4.1 Results from Simulations

In order to test the effectiveness of the contact-point response in identifying bridge frequencies, ten passages of the vehicle across the bridge were simulated, with speeds ranging from 1m/s to 10m/s. The axle response has previously been used by other researchers for the identification of bridge frequencies using the drive-by approach [8, 16], so results obtained from the contact-point response were compared to those obtained using the axle-response.

For these simulations, the pavement roughness was simulated by including a roughness profile for a ‘Class A’ pavement in accordance with ISO8608 [19]. The profile used in the simulations is shown in Figure 7.

It is noted that while many VBI models use a single point of contact between the vehicle model and the pavement surface, this may not be a true representation of the actual passage of the wheel over the pavement, whereby the wheel will not always touch the lowest points, or valleys, in the profile.

Due to the sensitivity of the contact-point response to the pavement roughness, a more realistic approach for modelling the path of the wheel over the pavement was adopted. The wheel was modelled as a rigid disk, with an outer diameter of 800mm, which only makes contact with the higher peaks in the pavement profile, using a similar approach to that adopted by Chang et al. [20]. The introduction of the pavement roughness into the simulations resulted in higher frequencies being present in the contact-point response and some signal processing was required to eliminate these frequencies from the response.

Figure 8 shows the frequency content of the axle response and the contact-point response for a 3m/s passage of the vehicle over the bridge. The scale of the FFTs have been normalised for comparison. It can be seen that the introduction of the pavement roughness into the simulation introduces additional frequencies. In particular, it can be seen that for the axle response, the axle-hop frequency of the vehicle is excited by the pavement roughness, and this masks the contribution of the bridge vibration to the overall response. For the contact-point response, it can be seen that the vehicle frequencies are not present in the signal, but the first three bridge frequencies can clearly be distinguished, demonstrating an improved ability to identify bridge frequencies over the axle response.

In order to assess the damage detection capabilities, varying levels of damage were simulated, using the approach outlined in Section 2.2, whereby a crack was induced at midspan. Damage levels were represented in terms of the crack depth as...
Table 3 lists the first three frequencies of the bridge, as calculated from the FE model, in the undamaged state and for each level of damage which was simulated. It can be seen that the second natural frequency remains almost unchanged, even for significant (40%) damage, whereas the first, and to a greater extent, the third, natural frequencies reduce more significantly with increased damage.

### Table 3. Natural Frequencies of Bridge (Hz)

<table>
<thead>
<tr>
<th>Damage Level</th>
<th>Mode</th>
<th>0%</th>
<th>5%</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.66</td>
<td>5.59</td>
<td>5.52</td>
<td>5.38</td>
<td>5.24</td>
<td>5.10</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>22.62</td>
<td>22.61</td>
<td>22.60</td>
<td>22.57</td>
<td>22.54</td>
<td>22.51</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>50.90</td>
<td>50.39</td>
<td>49.87</td>
<td>48.83</td>
<td>47.84</td>
<td>46.95</td>
<td></td>
</tr>
</tbody>
</table>

The results of the simulations showed that the identification of changes in the natural frequencies with damage were more accurate for lower speeds. In addition, it was shown that the vehicle frequency tended to dominate the axle response, very often masking the contribution of the bridge frequency to the response. Figure 9 shows the first natural frequency of the bridge as detected from the contact-point response and the axle response, comparing speeds of 1m/s and 7m/s. The solid black line represents the first natural frequency of the bridge calculated from the FE model (which is changing with increased damage) and the dashed black line represents the axle-hop frequency of the vehicle. The blue and red lines show the frequencies identified using the axle response and contact-point response respectively (solid = 1m/s, dashed = 7m/s). It can be seen that at the lower speed, the contact-point response is able to almost exactly capture the reduction in frequency which occurs with increasing damage, while the axle response, is often dominated by the axle-hop frequency of the vehicle (e.g. at 10% and 40% damage), which makes the bridge frequency indistinguishable in the response.

Examining the predictions made at 7m/s it can be seen than both the axle response and the contact-point response perform less accurately. At 7m/s the axle response is completely dominated by the vehicle vibration with the identified frequency always very close to the axle-hop frequency. No change in the detected frequency from the axle response can be observed with increasing damage. The contact-point response demonstrates the ability to capture the first frequency of the bridge quite well; however it is not able to capture the reduction in frequency which happens as the damage level is increased.

It should also be noted that as vehicle speeds increased, the contact-point response became dominated by the effects of the roughness of the pavement and no clear frequency could be distinguished. At speeds of 8-10m/s the contact-point response was unable to quantify any of the bridge frequencies, whereas the axle response showed a clear peak (similar to Figure 8) at the axle-hop frequency of the vehicle.

In order to give a better idea of the damage detection capabilities of the algorithm, the detected values for the first frequency of the bridge were averaged across all of the speeds that were tested (1-10m/s) to give an overall indication of the frequency predictions. Figure 10 shows a comparison of the frequency obtained from the axle response compared to that of the contact-point response. It can be seen that the contact-point response is capable of capturing the changing bridge frequency with damage, whereas the axle response predictions are biased towards the vehicle frequency and cannot capture the reduction in bridge frequency which occurs with damage.

It should be noted that the contact-point response results are biased towards the lower speeds (which give better results) because of the fact that it was unable to identify any dominant frequency at higher speeds, and these results are discarded from the predictions. The contact-point results would not perform as well if only higher vehicle speeds were used.
Figure 11 shows the detected values of the second and third frequencies by the contact-point response for increasing levels of damage. As before, values detected from all vehicle speeds (where a peak could be identified) were averaged to give the overall prediction at a given damage level.

It can be seen that the algorithm is capable of identifying the bridge frequency and can clearly identify the reduction in the third frequency which occurs with increasing levels of damage. As discussed previously, the second frequency is not significantly affected by damage at the mid-span and therefore the results using the second mode of vibration cannot be used as an indicator of damage.

4.2 Discussion of Results

The results of the simulations clearly show the merit in adopting the contact-point response to capture the bridge frequencies using a drive-by bridge monitoring approach. The results of this preliminary investigation do however highlight some limitations. The algorithm, as with many drive-by monitoring approaches, performs better at lower speeds and due to the effect of the pavement in the simulations cannot isolate bridge frequencies at higher speeds. The speeds of 1m/s-10m/s (3.6-36km/h) tested in this study would not allow damage detection at full highway speeds, which would be required in order for large-scale monitoring to be considered feasible using this approach. The contact-point response shows great promise in relation to the detection of higher bending frequencies of the bridge, which could be beneficial in cases where the type/location of damage does not have a significant impact on the first or primary vibrational mode of the bridge.

One of the advantages of the approach lies in the ability of the contact-point response to detect bridge frequencies without the influence of the vehicle frequency on the response, which is very often a major difficulty when implementing drive-by approaches.

As seen from the results, the changes in the natural frequency of the bridge may not be very large with increasing damage. Environmental factors such as temperature may also affect the frequency of the bridge without any damage or deterioration being present and these changes may cover up any changes in the dynamic behaviour which occur due to damage or deterioration. As such, additional testing, both numerical and experimental should be carried out to examine whether the approach could feasibly be extended to higher vehicle speeds and actual detection of changes in the bridge condition.

5 CONCLUSION

This paper develops a relationship between the measured response in a vehicle and the contact-point response between the wheel and the surface of a bridge in order to examine the feasibility of using the contact-point response as an indicator of damage. Results of numerical simulations show that the method is very effective at identifying the bridge frequencies and can also detect changes in bridge frequency when damage is simulated in a bridge.

The results show improved performance over using the measured response on the axle of the vehicle and show an ability to detect bridge frequencies without detecting the vibration of the vehicle in the response. The contact-point response is shown to perform poorly with increased vehicle speed and further work is required to investigate the feasibility of using the approach at full highway speeds.

The methodology presented in this paper shows promise as an indicator of bridge damage and should be explored further to test whether it could be practically implemented within drive-by bridge inspection regimes.

REFERENCES