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Direct Field Measurement of the Dynamic Amplification in a Bridge

Ciarán Carey¹, Eugene J. O’Brien¹,², Abdollah Malekjafarian², Myra Lydon³* and Su Taylor³

¹ Roughan & O’Donovan Innovative Solutions, Dublin, Ireland
² School of Civil Engineering and Earth Institute, University College Dublin, Dublin, Ireland
³ Queen’s University Belfast, Belfast, United Kingdom

* Corresponding author. Postal address: School of Planning, Architecture and Civil Engineering, Queens University Belfast, BT9 5AG, Northern Ireland. Phone number: +44 28 9097 4027 Email address: m.lydon@qub.ac.uk

Abstract

In this paper, the level of dynamics, as described by the Assessment Dynamic Ratio (ADR), is measured directly through a field test on a bridge in the United Kingdom. The bridge was instrumented using fiber optic strain sensors and piezo-polymer weigh-in-motion sensors were installed in the pavement on the approach road. Field measurements of static and static-plus-dynamic strains were taken over 45 days. The results show that, while dynamic amplification is large for many loading events, these tend not to be the critical events. ADR, the allowance that should be made for dynamics in an assessment of safety, is small.

Key words: field testing, bridge assessment dynamic ratio, fiber optic, weigh-in-motion

1. Introduction

Accurate bridge safety assessment requires knowledge of load effects as well as the structure’s capacity to resist these effects. Allowances for dynamic amplification of load effects are often conservative. Hence, better information on the magnitude of dynamic amplification has the potential to reduce the number of bridges that are prematurely repaired or replaced. This paper describes a study where the dynamic allowance for a bridge is directly measured on site.
Many studies have considered the dynamic impact factor for bridges subject to passing trucks [1-3]. The magnitude of the amplification of stress due to vehicle-bridge interaction (VBI) is often studied using the Dynamic Amplification Factor (DAF) [4-6]. DAF is defined as the ratio of the total load effect (including dynamics) to the static load effect for a particular loading scenario on the bridge. DAF has been used in many studies [7-12] for quantification of the dynamic increment of load effect on the bridge.

Paeglite and Paeglitis [13] present a study of the DAF obtained from the results of dynamic load tests of bridges carried out from 1990 to 2012 in Latvia. The DAF values were obtained from the dynamic response measured using an optical vibration sensor. The values of DAF obtained were analyzed and compared to the values used in the definition of the Eurocode 1 traffic load model. The actual DAF values for a good quality bridge deck surface were, in most cases, less than the values incorporated in the Eurocode [14].

O'Brien et al. [15, 16] suggest that DAF does not recognize the reduced probability of both maxima occurring simultaneously, i.e., static load effect and dynamic amplification. They point out that the maximum values of DAF tend to result from lighter vehicles and are not relevant when seeking characteristic maximum values and propose the concept of Assessment Dynamic Ratio (ADR). ADR is defined as the ratio of characteristic maximum total load effect, to characteristic static load effect, which, in general, correspond to different loading scenarios. For both total and static effects, the characteristic value is the expected maximum, over all possible cases, for the specified return period. This ADR is more appropriate for dynamic assessment since it provides the Engineer with the ratio of what is needed, to what can be found by static probabilistic analysis [17].

Previous research using ADR found the “expected level of lifetime dynamic interaction” for a certain site and bridge to be approximately 1.06, significantly lower than the DAF prescribed in the Eurocode [18]. González et al. [19] report that ADRs below 1.1 are typical for bridges with very good road profiles while González and Žnidarič [20] found that ADR, like DAF, tends to decrease with an increase in load. Both Enright at al. [21] and Caprani [12] state that the implication of such values for dynamics being much lower than expected is that the governing loading scenario for a majority of bridges is altered.

Caprani et al. [22] utilize multivariate extreme value theory in conjunction with static simulations and finite element vehicle-bridge dynamic interaction models to simulate static and total load effects for the Mura River Bridge in Slovenia. It is shown, for this bridge and traffic, that the required allowance reduces with increasing load effect. Consequently, the dynamic allowance is significantly less than recommended by bridge codes in this case.

Cantero et al. [23] extend the concept of ADR to railway bridges. Guidelines are provided in [24] and [25] on how to obtain a site-specific value for dynamic allowance,
both numerically and by field measurement. A Bridge weigh-in-motion (WIM) system was used to record the total response and to infer the static response of about 74 000 5-axle trucks over the course of a 58-day period. The measured total and inferred static bending moment for this population of vehicles is used to find the site-specific ADR value for a 50-year return period. It is shown that measured and numerically simulated data produce similar ADR values. However, it should be noted that, as static effects are inferred from the same sensors used to measure the total effects, there is a risk of bias. This risk is considered in [21] and numerical simulations suggest that the bias is small.

Whereas other investigations into ADR extrapolated the characteristic load effects using extreme value theory [16] simulated 10 000 years of traffic which allowed for an interpolation of load effects. It is reported in [24] that variability of ADR decreases as the sample size increases.

In this paper, a bridge structure is instrumented using fiber optic sensors and also a piezo-polymer WIM system. The static axle weights of passing vehicles are found using the WIM system and the corresponding static load effects found using the bridge influence line. The total load effects (including dynamics) are measured directly using fiber optic sensors on the bridge. The characteristic maximum total load effect and characteristic static load effect are found using the data has been collected through 45 days measurement for all vehicles weight more than 10 tons. The ADR value is found to be about 1.062 which is significantly less than the value which is normally considered for dynamic effects.

2. Weigh in Motion and Influence Line

2.1. Data Collection and Site

A bridge structure at Loughbrickland in Northern Ireland, United Kingdom (UK), was instrumented with fiber optic sensors. The bridge span is 18.8 m with a skew of 22.7° (Fig. 1). The beam-and-slab structure (Fig. 2) is typical of many short-span new-build bridges across the UK and Ireland. The superstructure consists of 27 no. prestressed concrete Y4 girders, each 1 m in depth, spaced at 1.22 m centers. The prestressed beams work compositely with a 200 mm overlaid cast in-situ concrete deck. The deck is supported by permanent glass reinforced concrete formwork, spanning transversely between the main beams. The abutments are supported by a pile cap which is integral with the deck beams.
The bridge structure forms part of the main Dublin to Belfast A1 road which was constructed in 2010. This route is ideal for an analysis of Heavy Goods Vehicles as it is an important link between the ports of Dublin, Warrenpoint and Belfast and forms a strategic cross-border economic link between Northern Ireland and the Republic of Ireland. The structure is on a central route through the island and has a high traffic volume. There are 10 000 to 12 000 vehicles travelling on the carriageway in each direction daily. The bridge also provides an underpass to give access to the southern end of the town of Loughbrickland. The traffic can pass under the main A1 carriageway and travel onto the B3 Dublin/Grovehill Road (Fig. 3).
The bridge carries four traffic lanes, two in each direction, as well as two peripheral lanes for traffic joining/exiting the carriageway, as shown in Fig. 2. A large central reserve separates the north- and south-bound carriageways; the northbound section was chosen for instrumentation.

Fiber optic sensors (MicronOptic 3200) with strain sensitivity of 1.2 micro strain were installed on Beam No. 6 (Fig. 2). These sensors use Fiber Bragg grating (FBG) technology. The advantages of FBG sensors for strain measurements are extensively documented in the literature \[26-29\]. Three sensors were installed in parallel, each on mechanical strain amplifiers as illustrated in Fig. 4. The mechanical amplifiers – simple plates in a 'dog-bone' shape – served the function of concentrating most of the movement over their 150 mm length at the sensor location \[28\]. The strains from three such amplifiers were averaged to further improve the resolution based on the suggestion made in \[30\]. A micron optics SM130 dynamic system was used for the data acquisition, the light source and interrogation elements are combined in one unit which allows for dynamic measurement of up to 1kHz. The unit outputs sensor wavelength data to an external computer via an Ethernet port, the shift in wavelength is then converted to change in strain as shown in Eq 1.

\[
\varepsilon = \left(\frac{\Delta \lambda}{\lambda_0}\right) \times 10^6 / F_g
\]

Where \(\varepsilon\) = strain, \(\Delta \lambda\) = wavelength shift, \(\lambda_0\) = Nominal wavelength, \(F_g\) = gauge factor.

Figure 3: Site layout.
The strain was output to the nearby control cabinet and saved for every six minutes of data. The scanning rate for the full system was set to 500Hz. There is a 6 second delay between the end of one record and the beginning of the next. A detailed description of the system can be found in [30].

![Image](image1.png)  ![Image](image2.png)

(a) (b)

Figure 4: Mechanical strain amplifiers (a) in place on the bridge, (b) bonding of strain gauge to amplifier.

A piezo-polymer pavement Weigh-in-Motion (WIM) system was embedded in the pavement on the approach to the structure (Fig. 5). The system can provide detailed information on the passing traffic including; gross weight, axle weights, axle spacings, temperature, speed and number of axles. The system takes the form of a Piezo-Loop-Piezo arrangement, a HI-TRAC TMU4 electronic unit with 2 lane configuration weigh-in-motion was used. The piezo sensors are used for weighing, when pressure is applied to the piezo-electric material an electric charge is produced. The sensor is embedded in a narrow strip of resin in the pavement and the load is then transferred through the pavement to the sensor. By measuring and analyzing the charge produced, the sensor is used to measure the weight of the passing wheel or axle group. This information was subsequently used for the estimation of static load effects for each loading event.

![Image](image3.png)

Figure 5: Overview of site and test structure.
2.2. Measured Influence Line

An influence line with high accuracy is required for the estimation of the static load effects for all events. The structure’s response to seven calibration trucks of known weight was used to infer the influence line from real measurements. One of the factors in choosing the site was the bridge’s proximity to a static weigh station located just outside Loughbrickland Village at its northern end. This weigh station is used by the Driver and Vehicle Agency of Northern Ireland (DVANI) to check the weights of vehicles using the dual carriageway. The gross vehicle weight (GVW) and axle weights of the calibration trucks were measured statically at the weigh station and are given in Table 1.

Table 1: Calibration truck properties.

<table>
<thead>
<tr>
<th>Truck No.</th>
<th>No. of axles</th>
<th>Gross weight (kg)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<tr>
<td>1</td>
<td>4</td>
<td>14 100</td>
<td>4200</td>
<td>3700</td>
<td>2900</td>
<td>3300</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>13 300</td>
<td>4800</td>
<td>3300</td>
<td>1800</td>
<td>1800</td>
<td>1600</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>24 500</td>
<td>5300</td>
<td>6500</td>
<td>4100</td>
<td>4400</td>
<td>4200</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>10 000</td>
<td>3900</td>
<td>3800</td>
<td>2300</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>8 700</td>
<td>4600</td>
<td>4100</td>
<td>-</td>
<td>-</td>
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<tr>
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<td>30 200</td>
<td>5800</td>
<td>8400</td>
<td>4000</td>
<td>5600</td>
<td>6400</td>
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</tr>
<tr>
<td>7</td>
<td>6</td>
<td>35 100</td>
<td>5600</td>
<td>2400</td>
<td>7100</td>
<td>6500</td>
<td>7000</td>
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The strain signal for Beam No. 6 due to the passage of Truck No. 1 is shown in Fig. 6. This was a Class 33 (4 axle rigid) 4 axle heavy goods vehicle travelling at 62km/h, the axle and gross vehicle weights are as presented in Table 1.

![Figure 6: Strain in Beam 6 due to Truck No. 1.](image)

To calculate the influence line corresponding to the passage of each calibration truck, the method developed by O'Brien et al. [31] is adopted. This uses the same principle
developed by Moses [32] to find unknown axle weight using a known influence line (Bridge WIM). An error function is defined as the sum of the squares of the differences between the measured and theoretical load effects:

\[ E = \sum_{k=1}^{K} (\varepsilon_k^M - \varepsilon_k^T)^2 \] (2)

where \( \varepsilon_k^M \) and \( \varepsilon_k^T \) are the \( k \)th measured and theoretical strains respectively and \( K \) is the number of data points (scans). The theoretical strain is a function of the axle loads and the corresponding influence line ordinates. In Bridge WIM the error function is differentiated with respect to the unknown axle weights and set to zero to minimize the error function. Here, the error function is differentiated with respect to each ordinate of the influence line. For the \( k \)th ordinate,

\[
\frac{\partial E}{\partial I_k} = 2[\varepsilon_k^M - (W_1 I_k + W_2 I_{k-t_2} + W_3 I_{k-t_3} + W_4 I_{k-t_4})](W_1) \\
+ 2[\varepsilon_{k-t_2}^M] \\
- (W_1 I_{k+t_2} + W_2 I_k + W_3 I_{k+t_2-t_2} + W_4 I_{k+t_2-t_2})(W_2) \\
+ 2[\varepsilon_{k+t_3}^M] \\
- (W_1 I_{k+t_3} + W_2 I_{k+t_3-t_2} + W_3 I_k + W_4 I_{k+t_3-t_2})(W_3) \\
+ 2[\varepsilon_{k+t_4}^M] \\
- (W_1 I_{k+t_4} + W_2 I_{k+t_4-t_2} + W_3 I_{k+t_4-t_3} + W_4 I_k)(W_4) = 0,
\]

where \( t_i \) is the number of data points between the passage of axles 1 and \( i \). Solving these linear equations in the \( K \) unknowns, \( I_k, k = 1, K \), gives the influence line which best fits the measured response. While Eq. (2) applies to a 4-axle truck, similar equations exist for trucks with other numbers of axles.

Information on the vehicle speed and axle spacing was taken from other sensors located in the pavement WIM system. A unit influence line for each of the seven calibration vehicles was found. The average of these values was then calculated and is illustrated in Fig 7. A moving average filter was then applied to the mean influence line, as proposed by González et al. [33] and this was deemed to be the final ‘measured’ influence line. As all of the calibration trucks traveled in the slow lane (lane 1 in Fig. 2), this influence line is only valid for trucks in that lane.
Figure 7: The unit influence line estimated from all seven calibration trucks.

3. Weigh-in-Motion data

Previous literature has indicated that data from piezo-polymer WIM systems is temperature sensitive and therefore is subject to a calibration drift over time[34]. The mean steer axle weight in standard 5-axle trucks was found to be correlated with temperature, suggesting that temperature compensation was not enabled in the system or it was not operating correctly. In addition, the distribution of steer axle weights for these trucks tended to decrease over time, even for trucks weighed at the same temperature. All the measurements for the steer axle weight of 5-axle vehicles, obtained at the temperature of $10^0 C$, have been plotted in Fig. 8. Different colors have been used to identify each individual month. However as the number of 5 axle vehicles occurring at a temperature of the $10^0 C$ varies across the months there is a significant variance in number of vehicle for each month.
Figure 8: Time drift of steer axle weights measured at 10°C (vehicles are given in chronological order; colors indicate different months)

The static response of Beam 6 to the passage of each truck is calculated as a linear combination of axle weights and the corresponding influence line ordinates from Fig. 7. To correct for temperature and drift, the calculated static response is scaled to best fit the measured total response. This is illustrated in Fig. 9. In effect, the WIM system is only being used to determine the relative weights of the axles of each truck while the fiber optic sensors are being used to determine the gross weight. The dynamic component is then defined as the ratio of the maximum measured total strain to the maximum scaled static strain.

Figure 9: Fitting of the static response to the total response.
4. Results and Discussion

4.1. DAF and ADR

The measurements were carried out from March 15th to April 28th, 2015. The WIM data and the measured strain data were gathered and synchronized. Only events with trucks heavier than 10 tonnes were considered. For reference, the DAF values are calculated for all the events measured through the 45 days and are shown in Fig. 10. The DAF values out of the range of 0.8 to 2.0 are removed as most of them are the result of error in the scaling process explained above. It can be seen that most values are in the range 0.9 to 1.6.

![Dynamic Amplification Factor (DAF) calculated over 45 days.](image)

Fig. 11 shows the plot of total versus static load effect for all the events. It illustrates that many of DAF values in Fig. 10 correspond to events with lower magnitude load effect. DAF is the slope of a line joining the origin to the point representing the event in Fig. 11. A linear regression to these points shows that the points are getting closer to the diagonal as the strains get larger, i.e., the mean DAF tends towards unity as strain increases.
Figure 11: Total versus static load effect. ADR is a function of the return period considered – the 99.9% ADR is the slope of a line joining the origin to the small circle.

The characteristic total with 99.9% probability of non-exceedance is 29.85 while the 99.9% characteristic static strain is 28.11. The ADR corresponds to the point where characteristic total meets characteristic static and is 1.062. This can be seen to be considerably less than the DAF values recorded (Fig. 10), which generally correspond to smaller strains.

The Beam 6 strains are plotted on Gumbel probability paper in Fig. 12. As expected, total strain exceeds static in general but there are a small number of exceptions. In particular, it can be seen that the 3rd, 4th and 5th largest static strains exceed the 3rd, 4th and 5th largest total strains. It should also be noted that there is a general trend of decreasing dynamics with increasing static load and this is expected [15, 16].

The changing slopes in the curves suggests data consistent with statistical mixtures of event types, likely corresponding to different types of truck. Best fit trend lines are fitted to each segment of data, as shown in the figure. The 99.9% characteristic values correspond to the final group of trucks (the heaviest ones), as can be seen in Fig. 12(b).
4.2. Conclusions

In this paper, the dynamic amplification at a point in a bridge beam is determined from field measurements. Dynamic Amplification Factor (DAF) and Assessment Dynamic Ratio (ADR) values are presented for the data measured during 45 days measurement. Total strain is measured directly using fiber optic sensors and static strain is measured from a piezo-polymer WIM system. A scaling process is used to remove the influence of temperature and drift in the static response. The WIM weights are converted to strains using an influence line inferred from the response to trucks weighed at a static weigh station. It is shown that in many cases DAF value is inappropriately high, driven by a large number of lighter trucks. On the other hand, the ADR is defined as the ratio of characteristic total to characteristic static strain. It is demonstrated that the ADR value is significantly less than the DAF values measured. While DAF value is normally considered as a measure of the dynamic amplification, it is shown experimentally that the ADR value is more effective and reliable. It can be concluded that by using ADR instead of DAF, a lower dynamic amplification can be considered in many cases. When this is taken into consideration at the design stage it can significantly reduce the construction cost of the bridge.

5. Acknowledgements

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Development Graduate Research Education Programme and Science Foundation Ireland towards this investigation under the US-Ireland Partnership Scheme. They also gratefully acknowledge the Driver and Vehicle Agency of Northern Ireland (DVANI) for providing the static weights of the calibration trucks.

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Figure Captions:
Figure 1: Side elevation of Loughbrickland site.
Figure 2: Section showing northbound carriageway.
Figure 3: Site layout.
Figure 4: Mechanical strain amplifiers (a) in place on the bridge, (b) bonding of strain gauge to amplifier.

Figure 5: Overview of site and test structure.

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Figure 12: Gumbel probability plot; (a) full plot, (b) a zoom view.