THE TEMPERATURE DEPENDENCE OF THE DYNAMIC AMPLIFICATION FACTOR




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Abstract

Bridge Weigh-in-Motion (B-WIM) systems transform the existing bridges or culverts from the road network into weighing scales, where the strains measured on a bridge or culvert superstructure are used to calculate the axle loads of the crossing vehicles. This data can be used for other purposes, including the evaluation of dynamic component of bridge traffic loading, the so-called Dynamic Amplification Factor (DAF) – the ratio between the dynamic and static load effects on a bridge. An FFT – based method has been recently developed and used to evaluate DAFs on a number of bridges. On several bridges the duration of measurement resulted in a large ambient and bridge temperature ranges. This paper presents the initial results of investigation into the possible temperature dependence of DAF. Data from two bridges were examined. It was observed that, although the temperature had an effect on both the static and dynamic components, their ratio stayed the same within the bounds of statistical error. These results indicate that DAF is temperature-independent. This is an important result, as it implies that there is apparently no need to account for possible temperature dependent changes in dynamic allowances in bridge safety evaluations.

Keywords: Bridge Weigh-in-Motion, Dynamic Amplification Factor, Temperature dependence

1. Introduction

The dynamic aspect of vehicle loading on bridge structures is typically considered by employing a Dynamic Amplification Factor (DAF) – a dimensionless coefficient representing the quotient of the dynamic load-induced effects relative to the static load-induced effects exerted upon a bridge. The FP6 ARCHES project (Gonzalez et.al. 2009) went into some detail about the dynamic effects of traffic on bridges. It provided an overview of the current design code recommendations for dynamic allowances and compared those with the simulations and with the measured allowances obtained using Bridge Weigh-in-Motion (B-WIM) (Moses 1979) measurements on several bridges. One of the more important conclusions was that the design code recommendations are generally conservative with respect to true dynamic allowance values, especially at higher (extreme) traffic loads. For structural assessment of existing bridges and, in many cases extending their lifetime, it is thus beneficial to apply more accurate methods of estimating dynamic allowances.

B-WIM systems transform the existing bridges or culverts from the road network into weighing scales (Corbally et al., 2014; Moses, 1979). The B-WIM algorithm uses the strains measured on a bridge or culvert superstructure to calculate the axle loads of the crossing vehicles. The structures are mostly instrumented with strain-measuring devices for a B-WIM installation. Traditionally, strains are acquired on the main longitudinal members of a bridge to provide response records of the structure under the moving vehicle load, but other locations can be used to improve the results. On slab bridges the strain sensors are typically mounted at the mid-span, across the entire width of the bridge, at regular intervals. Measurements during the whole vehicle crossing over the structure provide redundant data, facilitating the evaluation of axle loads.

Assuming that an inquiry into the potential temperature dependency of the Dynamic Amplification Factor (DAF) could yield significant advantages for long-term Structural Health Monitoring (SHM) applications, this manuscript will delineate a comprehensive analysis of DAF datasets. These datasets are derived from a sample of 15 bridge structures, encompassing two distinct categories: (1) beam and slab concrete highway bridges, and (2) highway underpasses constructed with steel I-girders and a reinforced concrete deck.

2. B-WIM for measurement of the dynamic amplification factor

B-WIM systems are not only used for weighing heavy vehicles but can, due to their data analysis architecture, provide additional information used for structural safety analysis (Žnidarič and Kalin, 2020), traffic load scheme development (Žnidarič, Turk and Kreslin, 2022) as well as DAF calculations (Kalin *et al.*, 2021).

2.1. Theoretical background for B-WIM

The first step in the weighing procedure selects and combines parts of a continuous stream of measured data into the so-called events, which contain signals from one or more vehicles whose influences on the bridge overlap. Axles of vehicles within events are then identified, their velocities calculated, and the individual axles joined into vehicles. Finally, the N unknown axle weights A_i in each event are calculated from a system of M equations

$$g(t_j) = \sum_{i=1}^{N} A_i I\left(v_i(t_j - t_i)\right); \quad j = 1 \dots M, \tag{1}$$

Where $g(t_j)$ are the bridge responses measured at M different times and $I(x) = I\left(v_i(t_j - t_i)\right)$ is the known influence line at location x. Axle velocities v_i and the arrival times of individual axles t_i determine the location of each axle at time t_j. The inputs from all strain sensors are ususally used, to minimise the influence of the varying transverse positions of vehicles. With the usual sampling rate of 512 samples per second and a typical vehicle crossing time of a few seconds, the number of equations is typically two orders of magnitude larger than the number of unknowns. This over-determined system of equations is solved for A_i, in the least-square sense, using the singular value decomposition algorithm (Press et al, 2007).

Influence lines are defined as the response of the bridge, at the sensor location, to the passage of a unit axle load. They are the critical structural parameter that directly affects the quality of B-WIM measurements. For the last 20 years, B-WIM systems use influence lines derived directly from the measured data on the site (Žnidarič and Lavrič, 2010; Žnidarič et al., 2010). The influence line calculation method developed at the Slovenian National Building and Civil Engineering Institute (ZAG) uses equation (1), where the function I(x) is also unknown and is calculated using Powell's minimisation technique (Press et al., 2007). The possibility of calculating actual influence lines is exceptionally beneficial in analysing of existing bridges (Žnidarič and Kalin, 2020). Details of the influence line calculation procedure are given in Žnidarič et al. (2017).

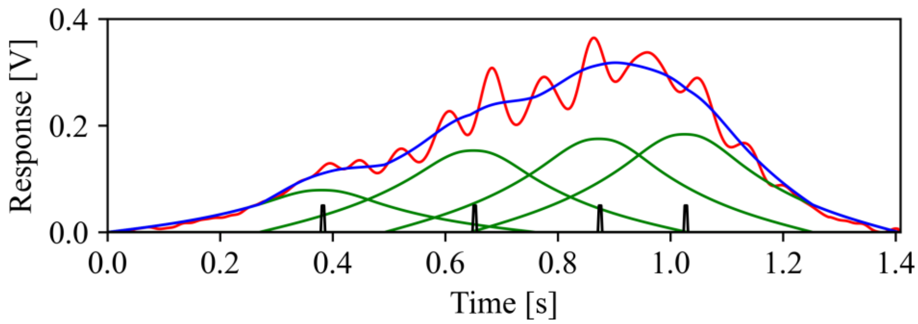

Figure 1 - An example of the result of B-WIM weighing

Figure 1 presents an example of weighing of a 40.5 t four-axle truck passing over a 10.5 m integral concrete slab bridge at 50 km/h. The red trace is the sum of measured signals, the black spikes are the positions of the four axles, the green traces are the influence lines at axle positions multiplied by raw axle loads and the blue trace is the sum of these axle contributions.

2.2. Measuring DAF with B-WIM

There are several definitions for the dynamic amplification, which can be described as the increase which occurs in the design load due to presence of dynamic components (Gonzalez et.al. 2009). In this paper the DAF will be defined as y_T/y_S, where y_T is the maximum total (static + dynamic) load effect due to a particular loading event and y_S is the maximum static load effect for the same loading event. Note that, with this definition, the maxima of total and static load effects need not coincide.

The total load effect is readily available – it is simply the measured response to a vehicle passage. However, the static load effect needs to be estimated from the total load effect. The method used in this paper assumes that the static and dynamic components of the load effect can be separated based on their characteristic frequencies (Gonzalez et.al. 2009). The characteristic frequency of the dynamic component is assumed to be higher than the frequencies present in the static component. The signal is transformed into the frequency domain using Fast Fourier Transform (Press et al., 2007), the spectrum low-pass filtered at a certain pre-determined cut-off frequency and transformed back into the time domain. Whatever remains is taken as the static load effect and used in the calculation of the DAF value.

The method used to estimate the static component uses FFT filtering to separate the measured signal into static and dynamic components, as proposed in the ARCHES project. To avoid the need for subjective determination of the cut-off frequency for the low-pass filter, the method used introduces two passes over the data (Kalin et.al. 2015). In the first pass the cut-off frequency for each individual event is determined by comparing the low-pass filtered signal with the theoretical signal, determined by the sum of influence lines multiplied by axle loads – the blue trace in Figure 1. Once the complete dataset has been processed, the mean cut-off frequency is used to filter the dataset again, this time using the low-pass filtered signal as the static signal approximation for the calculation of the DAF.

3. Temperature dependence of DAF

Observing the definition of DAF y_T/y_S, there are two possible causes of potential DAF temperature dependence: the change in static response and the change in dynamic response. At least for relatively simple concrete bridge structural systems, it is expected that the static response will increase with temperature, since Young's modulus is known to decrease with temperature. Thus the same stress (traffic loading) will cause an increase of strains. Different authors cite factors at around 0.3 %/K to 0.6 %/K (Yubo et.al. 2014).
The question that this paper will attempt to answer is whether the dynamic component increases in step with the static component, keeping the DAFs the same, or changes more or less than the static component, leading to increase or decrease of DAFs.

To enable the analysis of the dynamic component, one more quantity must be defined, y_D, which is the maximum of the dynamic component. This component is obtained by subtracting the static component from the measured signal, $g_D(t_i) = g_T(t_i) - g_S(t_i)$. Note that, due to non-linearity of the "maximum" operator, in general $y_D \neq y_T - y_S$.

3.1. Bridge selection and calculations

Two of the 15 bridges analysed in Kalin et.al. (2021) were chosen for initial temperature dependence analysis. The first (bridge A) is a single-span 34.4 m long concrete slab-on-girder type highway bridge where over 720,000 data points were collected during 15 months of operation. The temperature variation of 40 K, measured with a thermocouple inserted into a few centimetres deep hole in the concrete beam, was the highest among the considered bridges. In order to include a steel bridge, the second chosen bridge (bridge B) is a 3-span highway composite underpass made of six 1.8 m high steel I-girders and a reinforced concrete deck. The temperature variance during measurements was 20 K, measured with a thermocouple glued to a steel girder.

The data from both bridges was processed in accordance with the two-pass procedure. Table 1 summarises the results. The first two columns in the table are the bridge designation and the number of vehicles considered. DAF and σ_{DAF} are the mean measured DAF and the standard deviation, respectively. $T_{\min}$ and $T_{\max}$ are the minimum and maximum temperature values for the considered vehicles.

Table 1 – Summary of results

Site	N	DAF	σ_{DAF}	T_{min} [°C]	T_{max} [°C]	k_{DAF} [%/K]	k_S [%/K]	k_D [%/K]	Δ_{DAF}	$\frac{\Delta_{\text{DAF}}}{\sigma_{\text{DAF}}}$
A	728,094	1.08	0.07	-11.0	28.7	0.006	0.43	0.56	0.0026	0.04
B	27,847	1.18	0.15	16.2	36.1	-0.145	-1.96	-2.58	-0.0340	-0.23

A simple linear modeal was assumed for the temperature dependence of DAF and a linear regression of DAF vs T was performed. The next three columns are the linear coefficients for DAF, the static and the dynamic component, respectively. The units are percent change per Kelvin.

Taking a look at k_s, it is immediately apparent that the value 0.43 %/K for bridge A (concrete slab-on-girder type bridge) corresponds very well with the values from literature, 0.3 – 0.6 %/K. The increase in load effects is consistent with the expected change in Young's modulus. The value for bridge B, on the other hand, is quite larger and negative, meaning that the bridge stiffens with the rising temperature. It is out of the scope of this paper to determine the cause of this behaviour; however this behaviour was examined in more detail and confirmed to be true.

More importantly, the value of k_D, i.e., the relative dependence of the dynamic component, has the same sign and approximate value as the relative dependence of the static component. This results in a very small relative change of DAF with temperature. k_{DAF} is 0.006 %/K for bridge A and -0.145 %/K for bridge B. To gain some insight into these numbers, it is useful to consider the change of DAF over the whole measured temperature. The column Δ_{DAF} in Table 1 is simply $k_{\text{DAF}}(T_{\text{max}} - T_{\text{min}})$, the total change of DAF over the entire measured temperature range. In the column $\frac{\Delta_{\text{DAF}}}{\sigma_{\text{DAF}}}$ this value is compared to the standard deviation of DAF, which produces a measure of statistical importance of the measured temperature dependence.

It can be seen that the total change of DAF for bridge A is negligible compared to the standard deviation, just 0.04 or 4%. The relative change is larger for bridge B, -0.23 or -23%, but is still insignificant – less than a quarter of the standard deviation. This can be observed on Figure 2, where the dependence of DAF versus temperature is plotted for bridge B.

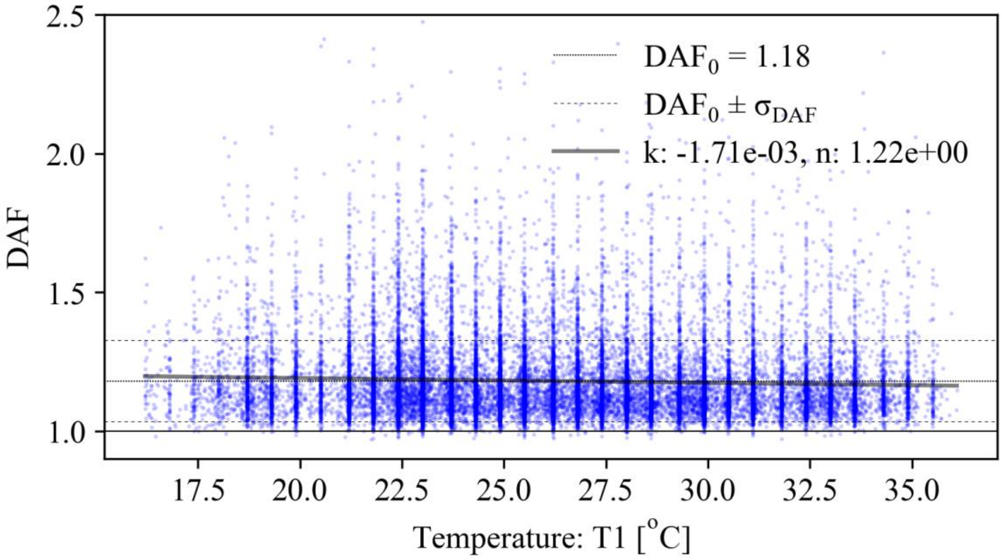

Figure 2 – Dependence of DAF on temperature for bridge B

The dotted line is the mean DAF, while the dashed lines are mean DAF ± one standard deviation. The thick grey line represents the fitted linear function, which can be seen to barely deviate from the mean DAF. It is also clearly seen that the fitted line is well within the standard deviation bounds and thus the temperature dependence of DAF is insignificant compared to the variance of DAF values themselves.

It can thus be concluded that, on these two bridges, DAF does not depend on temperature.

4. Conclusion

The temperature dependence of DAF has been investigated on two different bridges: a concrete slab girder-type bridge and a bridge featuring a concrete slab supported by steel I-girders. Comprehensive DAF calculations were executed for both bridges utilising the ZAG method.

The analysis revealed that the temperature dependence of the static load effect component for the concrete bridge aligns well with the anticipated decrease of stiffness of the bridge as temperature increases. Conversely, the steel bridge displayed a stiffening effect with rising temperature, which warrants further investigation for the explanation. Nevertheless, in both cases, the dynamic load effect component's variation closely mirrored that of the static component, resulting in an insignificant change in DAF.

The findings suggest that, for these two bridges, DAF values exhibit temperature independence. This implies that, at least for bridges with similar structural systems, accounting for potential temperature-dependent alterations in dynamic allowances may not be essential in bridge safety evaluations. However, it is crucial to note that the analysis was limited to only two bridges, and therefore, the conclusions should be interpreted cautiously. Future studies should incorporate numerical simulations, which would also considered different damage scenarios, and data from a more extensive selection of bridges to bolster the robustness of these findings.

5. Acknowledgement

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