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Experimental Determination of Dynamic Allowance for Traffic Loading in Bridges

Arturo González, BE, MSc, PhD, School of Architecture, Landscape and Civil Engineering, Newstead, University College Dublin, Belfield, Dublin 4, Ireland, phone: +353-1-7163219, fax: +353-1-7163297, e-mail: arturo.gonzalez@ucd.ie

Jason Dowling, BE, School of Architecture, Landscape and Civil Engineering, Newstead, University College Dublin, Belfield, Dublin 4, Ireland, phone: +353-1-7163233, fax: +353-1-7163297, e-mail: jason.dowling@ucd.ie

Eugene J. O’Brien, BE, MEngSc, PhD, CEng, FIEI, MIstructE, School of Architecture, Landscape and Civil Engineering, Newstead, University College Dublin, Belfield, Dublin 4, Ireland, phone: +353-1-7163224, fax: +353-1-7163297, e-mail: eugene.obrien@ucd.ie

Aleš Žnidarič, BSc, MSc, Slovenian National Building and Civil Engineering Institute, Dimiceva 12, SI-1000 Ljubljana, Slovenia, phone: +386-1-2804207, fax: +386-1-2804484, e-mail: ales.znidaric@zag.si

1corresponding author

Abstract. Bridge codes adopt values for dynamic allowance in traffic load models that are necessarily conservative to cover for an entire range of bridges with different mechanical characteristics, boundary conditions, and the large number of uncertainties associated to the vehicle-bridge interaction problem. A further level of conservatism occurs due to the independent manner in which the governing static load and the corresponding allowance for dynamics are specified. In particular, certain bridges are not susceptible to high levels of vehicle-bridge interaction when loaded by a critically heavy vehicle or a critical combination of vehicles. Recent advances in Bridge Weigh-In-Motion technology allow not only to collect information on the weights, spacings and speeds of the traffic loads traversing a bridge, but also to separate the maximum static strain from the total measured strain using a filtering procedure. In this paper, maximum static and total load effects are collected and analysed for three different sites as part of the European project ARCHES (6th RTD framework programme). Bridge measurements are used to discuss the dynamics of the most frequent truck classes and the entire traffic sample. The measurements reveal a decrease in percentage increment in dynamics and a reduction on the variability of the dynamic increment as the static load effect increases. This phenomenon can be of particular relevance in the assessment of the dynamics of extreme loading cases.

INTRODUCTION

When assessing the traffic load on a bridge, it is important to take into count the bridge code that was used in practice at the time the bridge was designed. An accurate assessment of the current traffic load may prevent a bridge from unnecessary strengthening or replacement, but it is necessary to account for the increases in heavy trafficking and variations in vehicle populations when assessing the capacity of such a bridge. There is also a large degree of uncertainty associated with the dynamic amplification caused by the interaction of the bridge with the imposed traffic load. It is common practice to use a dynamic allowance or a similar parameter to allow for the uncertainties associated with the structure, the material and the applied traffic load. AASHTO (1) defines a factor called Dynamic Load Allowance (DLA) that is applied to the static live load. DLA is shown in Equation 1, where $D_{sta}$ is the static live load effect, and $D_{dyn}$ is the increase in live load effect due to dynamics. The Eurocode (2) uses traffic load models with built-in Dynamic Amplification Factors (DAFs) that vary depending on the span length, number of lanes and load effect. DAF is presented in Equation 2. Both AASTHO and Eurocode traffic load models specify additional dynamic factors for individual components such as expansion joints. These load models are based on field tests and numerical simulations that cover a wide range of scenarios (3-5). If there was no site-specific information available to the engineer, these recommendations on dynamic allowance represent conservative values to follow.

$$DLA = \frac{D_{dyn}}{D_{sta}}$$  \hspace{1cm} (1)

$$DAF = \frac{Maximum\ Total\ Load\ Effect}{Maximum\ Static\ Load\ Effect}$$  \hspace{1cm} (2)
A more realistic characterization of the total load effect would require field measurements and/or the use of complex computer vehicle-bridge interaction (VBI) models. The extension of bridge load models to include dynamic VBI introduces a significant number of additional variables which require consideration if an accurate assessment of lifetime total load effect is to be carried out. A number of field tests have been carried out to analyze the dynamic allowance for varying load scenarios on various types of highway bridges (6,7). Similarly, numerous parametric studies have been implemented both experimentally and theoretically and have identified the importance of variables such as vehicle velocity, road surface roughness, bridge length or bridge frequency on the dynamic response. Of most interest however is the apparent trend of decreasing percentage of dynamic increment with increasing static load effect (8-11). The extensive experimental studies by SAMARIS (12) have reinforced this relationship. It seems clear that the site-specific total load assessment could be improved by examining the statistical occurrences of simultaneous high static loading and high dynamic interaction (13,14). The lower level of dynamics associated to the governing static loading cases form the basis for the recommendations given in this paper as part of the 6th European RTD framework ARCHES (Assessment and Rehabilitation of Central European Highway Structures, 2006-09) project (15). The ARCHES project involves partners from Belgium, Croatia, Czech Republic, Ireland, Italy, Poland, Slovenia, Spain, Switzerland and The Netherlands. Total and static strains have been measured using the Bridge WIM System, Si-WIM (16), and recommendations on dynamic allowance are provided for a number of bridge sites.

DYNAMIC AMPLIFICATION FOR CHARACTERISTIC STATIC LOAD EFFECTS

The methods of collection of traffic data using Weigh-In-Motion (WIM) technology have experienced significant advances in recent years (17-19) and they have facilitated to update site-specific bridge traffic load models. The various approaches to statically assess bridge traffic load and to determine the characteristic static load effects for a given return period have been described in the literature (20-23). Monte Carlo simulation of traffic flow is the most common method of bridge load assessment and the determination of those combinations of heavy vehicles contributing to bridge lifetime static load has been reported for different WIM sites (23,24). However, the analysis has been restricted to the consideration of maximum static load effect over some finite time period due mainly to the computationally expensive nature of VBI procedures that makes difficult to determine the true dynamic allowance. Dynamic amplification is typically considered following code recommendations that cover a wide range of scenarios. During the ARCHES project (2006-09), the authors have investigated this issue and they have provided guidelines on how to obtain a more accurate dynamic allowance for traffic loading on bridges. For this purpose, two concepts of dynamic allowance are employed: DAF and Assessment Dynamic Ratio (ADR) (14). DAF is defined here as the ratio of the maximum total load effect to the maximum static load effect caused by the passage of a vehicle or a number of vehicles over a bridge (Equation 2). In the latter, both total and static load effects refer to the same traffic loading event and to the same section in the bridge. ADR is the factor that multiplied by the characteristic static load effect will provide the characteristic total loading effect for a given return period (Equation 3). The characteristic total loading effect and the characteristic static loading effect do not necessarily correspond to the same traffic event.

\[
ADR = \frac{\text{Maximum Characteristic Total Load effect}}{\text{Maximum Characteristic Static Load effect}}
\]  

(3)

The recommendations provided in this paper are based on previous research using numerical VBI finite element models to determine dynamic amplification factors for critical traffic loading cases. Factors such as vehicle axle spacing, weight distribution, vehicle stiffness and damping characteristics have been shown to significantly influence DAF (3-14). These variables are generally quite uniform across the majority of a truck population. However site-specific variables such as vehicle velocity, vehicle weights and bridge characteristics such as bridge natural frequency, bridge damping and road surface profile can significantly affect DAF and consequently ADR. It is therefore apparent that allowance for dynamics may vary significantly for different bridges or different sites. There exists increasing evidence to suggest that the level of dynamic interaction decreases as the combined static live load applied to the bridge increases. This is in agreement with results from field tests in SAMARIS (12) and ARCHES (15). Although a large volume of research has been carried out into determining the combinations of vehicle and bridge parameters that cause high levels of bridge excitation a lack of knowledge currently exists regarding the levels of excitation associated to the total load effect at lifetime levels. González et al. (13,25) investigates the trend for critical traffic load at lifetime levels and they observe that DAF decreases for heavier vehicles and also that the variability of DAF for heavy vehicles is smaller than for light vehicles. It was also found that for the most critical events, the dynamic component of total load effect was very small and well below the
allowance provided for by the relevant design codes. In other related research (13), probability distributions were defined for vehicle weights, speed, distance between vehicles based on WIM data, and then used to obtain the characteristic value for static load effect and total load effect using Monte-Carlo simulation and numerical VBI models. For each simulated traffic event, maximum static and maximum total load effects were extracted. It was again observed that typically, the higher the static strain gets, the smaller DAF and the variability of DAF become. Finally, they obtained a site-specific dynamic allowance (ADR) from the cumulative distribution function of both load effects as shown in Figure 1. It is of interest that the characteristic static and total values (and hence, its ratio, ADR) may not necessarily arise from the same loading scenario. ADR will also vary depending on the return period being sought. The total load effect could be considerably smaller than the one derived from design codes if it was sought to extend the bridge lifetime for only a small amount of years. This procedure allows for an accurate assessment of lifetime total load effect on a specific bridge.

In practice, it is not possible to take measurements for the return period of the structure to produce the true ADR, but O'Brien et al. (14) show that a relatively short period of time can be used to give a conservative estimate of ADR. This is a consequence of the fact that longer measurement periods will lead to traffic events causing larger static responses, and larger static responses are typically associated to smaller percentage of dynamics. It was also found that as the return period increases, the influence of the road profile (or variability of ADR with the profile) decreases.

FIELD MEASUREMENTS
During ARCHES (15), theoretical simulations and site measurements have been carried out to establish a more accurate dynamic factor to employ in bridge assessment. The capability of the SiWIM system to measure maximum total strain and estimate the maximum static strain for each traffic event (16) is used to provide a site-specific recommendation for ADR. These recommendations are supported on the findings described in the previous section, where it became evident that it is possible to obtain a conservative estimation of ADR after a relatively short period of measurements. Then, the governing total load effect within a specified return period can be obtained multiplying ADR by the characteristic static load effect. The sites under investigation are two-lane bridges with traffic in opposite directions and they are defined in the table that follows:

Static Measurements
In addition to maximum static and total strain, Si-WIM collected information on the vehicle classes, weights and axle spacings. The two most frequent truck classes are the rigid 2-axle truck and the 5-axle articulated semi-trailer. Figure 2 shows the histograms of gross vehicle weights for these two classes in the Vransko site.

Distributions were fitted to the histograms as shown by the thick lines in the figures above. Tri-modal and bi-modal normal distributions achieved the best theoretical fit to the 5-axle and 2-axle WIM data respectively. The parameters of these distributions are given in Table 2. The higher modes represent the heaviest subclasses within a given truck configuration.

Dynamic Measurements
The theoretical investigations reviewed previously have shown that the dynamic allowance associated to the heaviest loading cases is clearly lower than the one associated to light vehicles. This can be experimentally verified with measurements of DAF and vehicle weights on site. Modern Bridge Weigh-In-Motion technology is able to provide a DAF value for each recorded vehicle event by filtering out the dynamic component of the signal due to bridge vibrations (16). It is acknowledged that there will be some degree of inaccuracy associated to the determination of the maximum static response which will depend on the sensor accuracy and characteristics of the site. Nevertheless, the inaccuracies will tend to provide conservative estimates of DAF due to the nature of the low-pass filter. That is, if part of the static response was unintentionally removed as result of using the 1st main frequency of the bridge as cut-off frequency, the maximum static strain and DAF will be underestimated and overestimated respectively. Figure 3 show the relationship between DAF and maximum static strain for two different bridge sites. Values in bridge codes would suggest a higher DAF for both bridges (i.e., 1.27 and 1.2 for Trebnje and Vransko respectively according to Eurocode, and 1.33 according to AASHTO), but evidence shows that for the heaviest vehicles, the maximum DAF will not exceed 1.1 (represented by a horizontal dotted line in Figure 3). The mean and 90% confidence intervals of DAF are calculated every 10 microstrains and represented in the figure to illustrate the decrease in DAF trend. The smaller scatter of the tail associated to the maximum static strains of these figures resemble the theoretical findings (13,14,25) associated to critical loading cases.
Distribution of DAF by Vehicle Classes
A vast amount of dynamic measurements were taken during the period of measurements described in TABLE 2. 2-axle and 5-axle trucks were the dominant truck classes and using the mean and standard deviation values of the distributions defined in Table 2, the five vehicle subclasses (5-axle: 1st mode, 5-axle: 2nd mode, 5-axle: 3rd mode, 2-axle: 1st mode & 2-axle: 2nd mode) were extracted from the data and analyzed separately. Taking these new data sets of each subclass, histograms of DAF values are shown in Figures 4(a), (b) and (c). The results are well defined, with the exception of The Netherlands ‘5-axle - 2nd mode’ data set where there are two distinct peaks in the DAF distribution. This would seem to suggest that there may be two, quite different velocity distributions within this subclass, or also perhaps loaded and unloaded trucks of this same subclass. The figures below are found in agreement with previous investigations indicating that: (1) Larger DAFs are associated to lighter vehicles (lower modes) and (2) Larger DAFs are associated to vehicles with smaller number of axles.

EXPERIMENTAL DETERMINATION OF DYNAMIC ALLOWANCE
This section compares the maximum total and static strains collected in the field with emphasis on the larger loads. Gumbel plots are generated for entire data sets and also vehicle subclasses. Then, these plots are used to represent the ith total strain over the ith static strain for the event i when all bridge measurements are ranked in order of increasing strain. The tail of the latter can be used to obtain an estimation of ADR and its variability.

Analysis of Daily Maximums
Figure 5 shows a plot of the maximum estimated static strain and the measured total strain per day on Gumbel probability paper, seeking the underlying trend of the data in the Vransko site. Due to insufficient data and the mixture of vehicle traffic events, this figure contains kinks, that makes the extrapolation to extreme values, such as characteristic 75-year or 1000-year values, difficult to establish.

This leads to the next stage of analysis, isolating vehicle classes for which there exists sufficient data to identify a more reasonable trend in DAF ( & ADR). The vehicle classes chosen for this are the 5-axle and 2-axle higher modes described in Table 2. Gumbel plots were once again calculated representing each subclass separately in Figure 6. If a small percentage of the data was removed from either end of the plots, a trend becomes apparent where static and total strain are nearly parallel, i.e., the relative dynamic increment with respect to the static load effect tends to decrease. This phenomenon also appears in the other subclasses and sites.

Estimation of a Conservative ADR
In Figure 7, ADR is plotted versus rank number for different vehicle subclasses in the Vransko bridge (i.e., the ratio of worst possible total load effect divided by worst possible static load effect for a given vehicle subclass and rank number). The maximum total and static strain generated by the each vehicle is taken into count in these graphs. The sample is ranked by order of increasing strain and then, the total over the static strain (or ADR) is calculated for each point. This is not exactly ADR as defined in Figure 1, but an approximation limited by the sample size, although theoretical investigations seem to indicate this approximation is conservative (13). There is a clear trend for ADR and the variability of ADR to decrease as the rank number (or sample size) increases, except for boundary errors appearing at the extremes (these could be due to outliers, vehicles changing lanes or some kind of interference that corrupted the measurements). As expected, ADR appears to be smaller for the heaviest vehicle subclass (5th axle, 3rd mode). When analyzing all bridge sites, it has been observed the 3rd mode subclass of the 5-axle truck (the heaviest vehicle subclass under investigation) produces the lowest ADR value of all vehicle subclasses. Therefore, the trend in ADR for the 3rd mode subclass of the 5th axle gets nearly horizontal for the heaviest vehicles due to the larger available sample for this mode and also, the smaller variability of dynamics associated to heavier modes.

Figure 8 compares the ADR of the 3rd mode subclass of the 5-axle vehicle for the three sites. If edge errors were ignored, once the sample is large enough -as for the Vransko bridge-, the ADR does not oscillate as much and tends towards a lower bound value. Further indicating that as load effect increases, ADR reduces.

Finally, Figure 9 compares the ADR of the three sites when considering the full data set (all vehicles). It can be seen that Figure 9 exhibits more oscillations than Figure 8, since the sample of heaviest vehicles is reduced and not as representative as for the 5-axle vehicle class. If the duration of the measurements is limited, it may not be possible to gather enough information on the dynamic amplification associated to the critical loading cases causing larger strains (denoted by the presence of oscillations in the tail). However, there are vehicle classes such as the 5-axle articulated truck traffic event which occur frequently and their dynamic behavior can be accurately characterized. For the three sites, it appears that the heavy (3rd mode) 5-axle vehicle class provides a conservative estimation of what the ADR associated to the heaviest critical loading cases may be. This is supported by numerical
simulations carried out in ARCHES (15) showing that the dynamics associated to critical static loading cases are smaller than those associated to typical 5-axle European trucks.

The general trend from all these plots is in agreement with previous theoretical findings that show ADR is generally reducing with increasing load effect. There exists greater variability in the earlier stages of ADR versus load effect (smaller return period) plots, but the trend remains invariably downwards. For very low rank values and for the uppermost values these plots become slightly erratic. It is worth noting that these ADR figures contain all of the data points, i.e., no events have been removed which have given questionable results (i.e., relatively high strains for relatively low gross vehicle weights or viceversa). In the three sets of site data analysed here, ADR value for the largest bridge responses was always less than 1.10, which it is lower and more realistic than the values recommended by the code for the bridges under consideration (1,2) if an accurate assessment of the effect of the traffic loads on the bridge is sought. The question remains however, in the duration of measurements necessary to capture the variability of ADR. Previous theoretical studies (14) have proposed five or ten 5-week sets of measurement and using the mean + 1.64 standards deviations (corresponding to a 95% confidence interval) as a reasonably accurate and generally conservative estimate of the 1000-year ADR value.

CONCLUSIONS
Bridge measurements and site specific assessment of traffic loading has considerable potential to prove the safety of a bridge that would otherwise need to be rehabilitated or replaced. In particular, bridge standards are conservative when covering the dynamic amplification due to the wide range of possible traffic loading, road and bridge conditions throughout the network. For short- and medium-span bridges, the road profile is one of the parameters introducing a larger degree of uncertainty in the dynamic response. If the bridge surface and approach was maintained in a good condition, the dynamic amplification associated to the critical loading cases could be substantially reduced in relation to the values employed by traffic load models. The magnitude of this reduction is site-specific and needs to be confirmed with site measurements as presented here, and vehicle-bridge interaction models. A parameter defined as ADR has been used to characterize the total load effect for a given return period as a function of the critical static load effect. Experimental and simulation data obtained in the European project ARCHES has shown that in the case of very good road profiles, the critical loading cases governing the maximum load effects are typically associated to ADRs below 1.1.

ACKNOWLEDGEMENTS
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FIGURE 9 ADR versus rank number for the full data set in the three bridge sites.
### TABLE 2 Site Characteristics

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<td>112,339</td>
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## TABLE 2 Parameters for Fitted Distributions

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<th>Site</th>
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