Bridge Traffic Loading: The Implications of Some Recent Findings

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Abstract

The maintenance of highway infrastructure requires major expenditure in many countries. By minimizing the repair or replacement of highway bridges in particular, this cost can be reduced significantly. Of the two bridge assessment components, loading is more difficult to estimate than strength, due to its more variable nature. Consequently, bridge traffic loading has been an area of intensive research in recent years. Recent research has focused on assumptions inherent in previous work and the results are presented and discussed.

In this paper, the latest statistical analyses adapted for use in the bridge traffic loading problem are reported. Comparisons to the previous state of the art are made and it is shown that a revised approach reflects the underlying phenomenon of bridge traffic loading more accurately. A method which is shown to reduce the variability of the statistical extrapolation process is also presented. Of more significance, a statistical approach which joins the dynamic and static effects of traffic loading is presented. An assumption inherent in much previous research in this area is that free-flowing traffic with coincident dynamic effects is more critical than congested traffic (which has practically no dynamic effect) for short- to medium-length bridges. Given that about 90% of bridge stock is of this length, this assumption has critical implications for the expenditure on bridge rehabilitation. A sample application of the proposed statistical method is presented and the results are shown to be of great significance. It is shown that the level of dynamic interaction is not sufficient for free-flowing traffic to govern and that it is congested traffic that may govern the vast majority of bridges.

The implications of the cumulative effect of these various findings are discussed with reference to the future direction of research into bridge traffic loading and current practice in bridge assessment for traffic loading.

Keywords: Bridges, Loading, Statistics, Simulation, Traffic, Trucks

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INTRODUCTION

Background

The maintenance costs associated with ageing bridge stocks across the world represent an increasing proportion of total road infrastructure expenditure. The EU expenditure on the repair, rehabilitation and maintenance of bridge structures is estimated to be €4–6 bn annually [1]. As only the 15 member states up to May 2004 are included in this estimate, in the recently-enlarged EU, bridge maintenance expenditure is likely to be more than €6 bn annually.

As a result of the high maintenance cost, research into the assessment of existing infrastructure has received great focus recently. This is so, as significant savings are possible, through more accurate modelling of both the physical and statistical phenomena associated with the problem. In particular, given that bridge traffic loading is significantly more variable than bridge capacity, it is in this area that much progress towards reducing maintenance expenditure may be made.

The focus of this paper is to present some recent findings in the statistical analysis of bridge traffic loading, and to discuss their implications. These recent findings are briefly compared to relevant reports in the literature. The implications of these findings to ongoing research and the practical assessment of existing bridges are also discussed.

Basis of Research

Modelling bridge traffic load effect requires the input of actual highway traffic data, obtained from suitable installations. Weigh-In-Motion (WIM) technology is frequently used for this purpose. The work reported here is based on measured traffic from the Paris to Lyon A6 motorway near Auxerre, France. The site has 4 lanes of traffic (2 in each direction) but only the traffic recorded in the slow lanes was used (it is acknowledged that this results in conservative loading for a 2-lane bridge, for example). In total 17 756 and 18 617 trucks were measured in the north and south slow lanes respectively, giving an average daily truck flow of 6744 trucks. It is important to note that though the particular results may be influenced by the quantity of data available, the methodologies presented in this work are general.

Monte Carlo simulation of traffic streams is based upon the measured traffic from a given site. The bridge loading induced by such a traffic stream is then obtained by using influence lines (whether theoretical, site-measured, or obtained from finite-element modelling of the bridge) for the load effect of interest. Detailed information on the simulation process used to obtain the results herein is described by Caprani [2] and OBrien and Caprani [3]. Of relevance to this paper, as only hourly variations in traffic flow and composition are modelled, the statistical models are only stationary once inference is based on data of at least 24 hours' duration. In addition, it is taken that the 'economic year' is equivalent to about 50 weeks of weekday traffic and consequently 250 'simulation days' are taken to represent a calendar year.

STATIC TRAFFIC LOAD EFFECT

Statistical Methods in the Literature

Overview

There have been many different methods used to predict the lifetime bridge load effect from measured or simulated load effect data. Caprani [2] presents a review of these methods, which are briefly summarised here.

In a series of studies by Nowak and others (see [4]–[6] for example), straight or curved lines are superimposed on the tails of the distributions and extrapolated to determine the characteristic load effect values. As part of the background studies to the Eurocode for bridge loading [7], Bruls et al [8] and Flint and Jacob [9] consider and compare several methods of extrapolation of the basic histogram of load effect, based on measured traffic samples. A weighted least-squares approach is used by Grave et al [10] to fit Weibull distributions to load effect values. Castillo's [11] recommendation to use upper $2\sqrt{n}$ data points is adopted by Grave et al [10]. Bailey and Bez [12, 13] determine that the Weibull distribution is most appropriate to model the tails of the load effect distributions and used maximum likelihood estimation, whilst Cooper [14, 15] uses measured truck loading events to determine the distribution of load effect. Cooper raises this distribution to a power to establish the distribution of the maximum load effect from 4.5 days of traffic. This is fit with a Gumbel distribution which is used to extrapolate to a 2400 year return period. Of a more statistically advanced nature is the work of Crespo-Minguillón and Casas [16] who adopt a Peaks-Over-Threshold approach and use the Generalized Pareto Distribution to model the exceedances of weekly maximum traffic effects over a certain threshold.

Problems

The attributes required of a robust statistical extrapolation procedure are described by Caprani [2] and summarised here. Of most importance is that a model should not be subjective: different results obtained as a result of different processing decisions do not induce confidence in any of the results. Other requirements are as follows:

- *Choice of Population:* The population upon which the analysis is based must be in keeping with the limitations of the statistical model to be applied. In many cases the stationarity assumption of many statistical models is violated.
- *Distribution of Extreme Load Effects:* Often decisions about which extreme value distribution to use are made. This is unnecessary given that the Generalized Extreme Value distribution incorporates all three.
- *Estimation:* The means by which the model parameter estimation is done is often graphical or least-squares-based when more accurate methods, such as maximum likelihood estimation exist.
- *Choice of Thresholds:* Many authors make decisions regarding the data which is to be kept as a basis for the analysis – the 'tail' data problem. This is unnecessary if the correct model is being applied to the correct population using good estimation procedures.

Save for that of [16] other means of extrapolation generally fail to meet the minimum requirements of a statistical model. Also, variability of the characteristic load effect is not generally assessed. Extrapolations are carried out to the return period, rather than to find the actual characteristic value (which for the Eurocode for bridge loading [7] is 10% probability of exceedance in 100 years).

Recent Advances

The Statistical Nature of Bridge Traffic Load Effect

Recent work [17] has concluded that bridge traffic load effect is not a single statistical generating mechanism. In essence and as is intuitively reasonable, the distribution of load effects caused by a 2-truck event (two trucks concurrently present on the bridge) differs to that of a 3-truck event. When each loading event-type is isolated, it is found [2] that the Generalized Extreme Value Distribution (GEV) is appropriate to model the daily maximum load effects that result. Therefore a composite distribution of daily maximum load effect, $\overline{S}$, is required as a basis for extrapolation. An appropriate generalized extreme value composite distribution model, $G_C(\cdot)$, is described by Caprani et al [17] to be:

$$P\left[\overline{S} \le s\right] = G_C(s) = \prod_{j=1}^{N} G_j(s) \quad (1)$$

where $G_j(\cdot)$ is the GEV distribution of the *j*th of *N* possible event-types. This model has been shown to exhibit greater fidelity in fitting distributions of load effect, and meets minimum requirements for a good extrapolation model [2].

Predicting the Lifetime Load Effect

Extrapolations to a return period result in a single value of load effect. This is statistically flawed: repeating the process would generally yield a different result. Thus it may be thought that there exists a distribution of characteristic values, but this is not necessary. Instead, the definition of characteristic value should be unequivocal, as is that, for example, of the Eurocode [7]. Therefore focus should be centred on the estimation of the lifetime distribution of load effect, from which the characteristic value is then derived. Of significant further value would be a means by which allowances for modelling uncertainties, such as parameter confidence intervals, could be included.

Predictive likelihood is a method for estimation which allows both for sampling and modelling uncertainties. Caprani and OBrien [18] have applied this method to the bridge loading problem and shows that the traditional return period approach yields different results to the direct estimate of the characteristic value from the lifetime distribution of load effect [19]. The method has also been shown [20] to be effective in predicting extreme vehicle weights.

Comparison

The net effect of the application of the two advances described, in comparison to a statistical model which represents the best of the models in the literature, is shown in Fig. 1 for three load effects:

- Load Effect 1: Bending moment at the mid-span of a simply supported bridge;
- Load Effect 2: Left support shear in a simply-supported bridge;
- Load Effect 3: Bending moment at central support of a two-span continuous bridge.

From Fig. 1 it can be seen that the differences are generally small, with notable exceptions for spans of about 40 m. In particular, Load Effect 2 is sensitive to spans around 40 m due to the shape of its influence line, and the inter-vehicle gaps. That the differences are not excessive, despite the advances in analysis, shows a certain degree of robustness amongst the better statistical extrapolation methods. Caprani [2] describes these differences in more detail.

A difference in load effect of up to 14% is substantial when existing bridges fail assessments by only a few percent. As a result substantial savings are possible, not only in materials and labour, but more importantly through a reduction in traffic disruption.

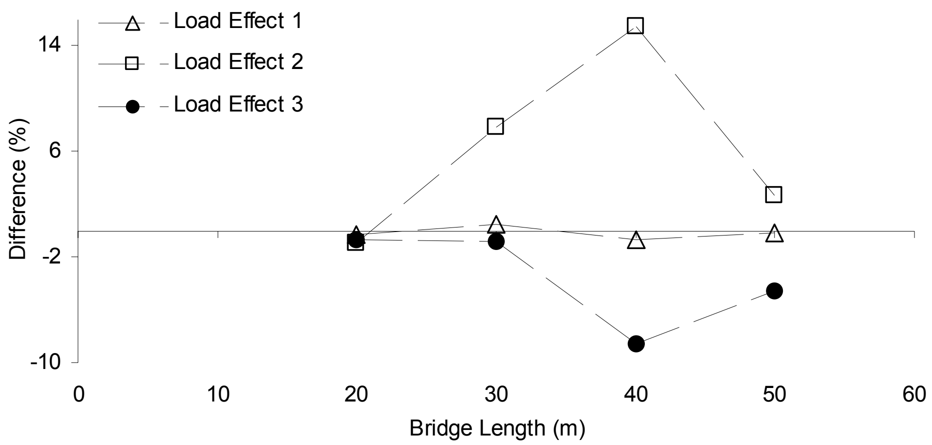


Fig. 1 Change in Predicted Load Effect Due to Recent Advances

TRAFFIC LOAD EFFECT ALLOWING FOR DYNAMIC INTERACTION

Incorporation of Dynamic Effects into Bridge Traffic Load Models

The dynamic amplification factor (DAF) is defined as the ratio of total to static load effect, where total load effect results from the truck and bridge interacting dynamically, in addition to the static load effect. Allowances for dynamic interaction are made in bridge loading codes, based on the notion of the DAF. Usually however, the worst possible DAF is applied to the critical static load effect. This does not take into account the reduced likelihood of these events coinciding. Indeed it is intuitively reasonable that grossly overloaded vehicles are not as dynamically lively as unloaded vehicles, for example. The conservative loading that results from the application of a critical DAF to a critical static load effect has been an area of active research in University College Dublin in recent years.

Recent Advances in Dynamic Interaction Modelling

Advances in knowledge and technology have led to increased accuracy in the assessment of the dynamic bridge-vehicle interaction that occurs for given bridge loading scenarios. A number of experimental studies on the dynamic loading of beam and slab (girder) bridges have been carried out previously [21, 22]. These studies reveal that a reasonable level of accuracy may be achieved using simplified planar beam, or grillage models. However, more complex three-dimensional finite element approaches yield more accurate validations, and allow for the investigation of numerous varying bridge load effects [22, 23, 24].

Also of importance are computationally-efficient methods for the estimation of bridge-traffic dynamic interaction. Significant advances have been made with such models in recent years. In particular, numerically efficient solutions have been developed to determine the influence of vehicle speed and road irregularities at particular points on the road and have been shown to be reasonably accurate [25].

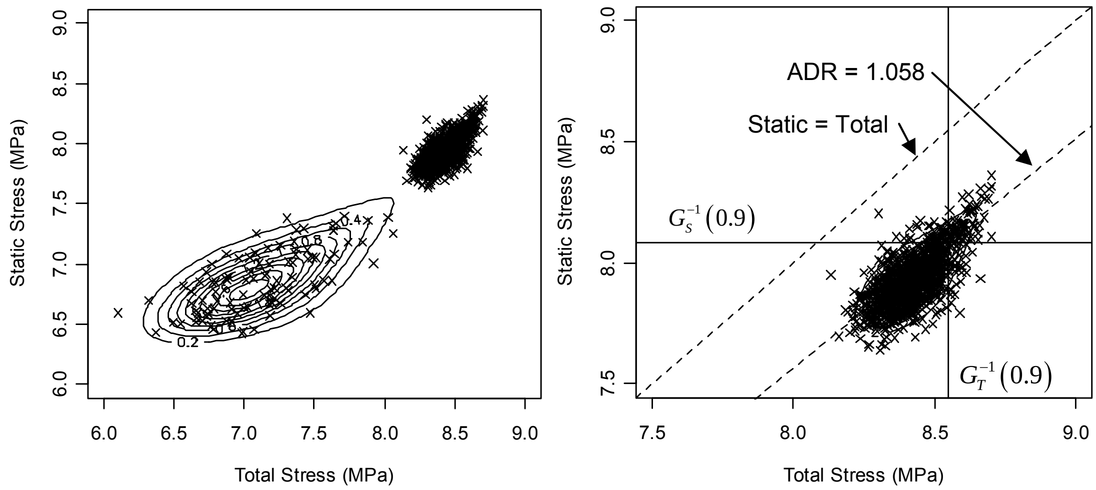
Predicting the Level of Dynamic Interaction for the Lifetime Load Effect

<u>Statistical Background</u>

Total and static load effects are related through the DAF, which is not constant but there remains a degree of correlation between these statistical variables. The recent statistical theories of multivariate extreme values has been applied to this problem to extrapolate these correlated variables to their design lifetime values. Their ratio at this level is therefore the level of dynamic interaction applicable for the bridge design lifetime. This has been termed the assessment dynamic ratio (ADR) by Caprani et al [26] in recognition that it does not arise from any one single loading event.

Sample Application

The Mura River bridge in Slovenia is used to provide a sample application of the statistical analysis for ADR. Monthly maximum load effects were identified from static simulations. These were then modelled to determine the level of dynamic interaction [23]. The population of total and static load effects were then processed statistically, an illustration of which is in Fig. 1 and is described by Caprani [2]. As can be seen, the expected level of lifetime dynamic interaction, for this site and bridge, is a DAF of about 1.06. This is significantly less than the DAF allowed for in the Eurocode of about 1.13 for such a bridge.



(a) Parent and Extreme Populations **(b) Lifetime Total and Static Load Effect**

Fig. 2 Multivariate Extreme Value Extrapolation for Lifetime DAF.

THE IMPLICATIONS OF RECENT FINDINGS

Implications for the General Bridge Traffic Load Effect Problem

The recent findings outlined previously have significant implications for both the actual assessment of lifetime load effects, as well as the direction of future research needs. The importance of the finding in relation to lifetime DAF is particularly relevant given that the majority of bridges are of short- to medium-length. Currently it is taken that the governing loading scenario for these bridges is that of free-flowing traffic with associated dynamic effects. The very low lifetime dynamic allowance found for the Mura River bridge, if found to be general, will alter the governing loading scenario for the vast majority of bridges. These points are summarised in Fig. 3.

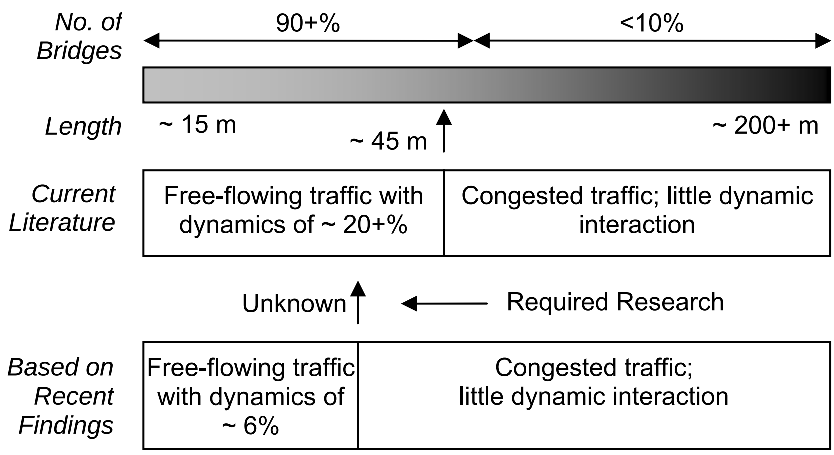


Fig. 3 Governing loading scenarios for different bridge lengths.

The Future Direction of Bridge Traffic Load Research

A clear need for further research is evident from Fig. 3. For a wide range of bridge-lengths, load effects and dynamic parameters (such as pavement roughness) it will be required to determine the governing loading scenario, be it congested traffic (with little dynamics) or free-flowing traffic (with some dynamics). To complement this, further advances in the computation of dynamic interaction, in addition to those reported, are required. This is so in order that traffic simulations could incorporate dynamics as the simulations progress, instead of requiring time-consuming post-processing outside the simulation. In addition, the statistical methods recently introduced need to be further advanced. For example, a multivariate peaks-over-threshold approach would avoid the need for decisions as to block and population size. Indeed, if dynamic interaction is subsequently found to play only a small part in bridge lifetime loading, reductions in loading are more likely to come from advancing the statistical analyses applied to the problem.

The Assessment of Existing Bridges

In many countries there is little scope for bridge assessment consultants to operate outside codes of practice. Indeed bridge authorities are necessarily conservative in their approach to bridge maintenance. The remarkable benefits that the ongoing research into the bridge loading problem can bring must therefore be brought to the attention of bridge owners and consultants. Concurrently, codes of practice must be updated, and where possible, provision made for the possibility of using proven state-of-the-art methods. It is only through such measures that the ultimate goal of research like that presented here will find fruition.

CONCLUSIONS

Some recent findings in bridge traffic loading are outlined. It is shown that advances in the statistical methods applied to estimating lifetime static load effect have resulted in differences to previous practices by as much as 14% at least. This method takes into account sampling and modelling uncertainty as well as the composite nature of bridge loading.

A new statistical approach to estimating the level of lifetime dynamic allowance required is discussed. It is shown that for a sample application, this method returns a lifetime dynamic allowance of about 6%, significantly lower than that allowed for in current bridge loading codes. This has significant implications for the majority of bridges, because a different loading scenario governs to that catered for in bridge traffic loading codes.

The implications of these recent findings for the assessment of existing bridges and for ongoing bridge loading research are briefly discussed. Suggestions as the possible directions of forthcoming bridge traffic load research are made.

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