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A review of probabilistic methods of assessment of load effects in bridges

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ABSTRACT

This paper reviews a range of statistical approaches to illustrate the influence of data quality and quantity on the probabilistic modelling of traffic load effects. It also aims to demonstrate the importance of long-run simulations in calculating characteristic traffic load effects. The popular methods of Peaks Over Threshold and Generalised Extreme Value are considered but also other methods including the Box–Cox approach, fitting to a Normal distribution and the Rice formula. For these five methods, curves are fitted to the tails of the daily maximum data.

Bayesian Updating and Predictive Likelihood are also assessed, which require the entire data for fittings. The accuracy of each method in calculating 75-year characteristic values and probability of failure, using different quantities of data, is assessed. The nature of the problem is first introduced by a simple numerical example with a known theoretical answer. It is then extended to more realistic problems, where long-run simulations are used to provide benchmark results, against which each method is compared. Increasing the number of data in the sample results in higher accuracy of approximations but it is not able to completely eliminate the uncertainty associated with the extrapolation. Results also show that the accuracy of estimations of characteristic value and probabilities of failure are more a function of data quality than extrapolation technique. This highlights the importance of long-run simulations as a means of reducing the errors associated with the extrapolation process.

1. Introduction

A necessary part of bridge management is assessment of the safety of bridge structures. In its simplest form, a bridge is safe when its capacity to resist load exceeds the load applied. More precisely, a bridge can be considered safe when there is an acceptably low probability that load exceeds capacity. A great deal of work has been carried out on methods of evaluating the load-carrying capacity of bridges and the associated uncertainties. Load-carrying capacity can be reduced by different forms of deterioration, depending on factors such as the structural material, the quality of workmanship during construction, the age of the structure, the environment and the loading history. To carry out a more accurate assessment of the load-carrying capacity, non-destructive and/or destructive tests can be carried out to get more detailed site specific information on these deterioration mechanisms to reduce uncertainty and associated conservatism [2,42,88,90,96]. These inspection results can be incorporated into time-dependent reliability-based assessments to give up-to-date structure-specific deterioration rates. These in turn can be used to accurately predict the capacity of the structure and to schedule maintenance and repairs [66,84,85,91].

Traffic loading on bridges, one of the great sources of uncertainty, is the focus of this paper. In this study, historical developments in the field of traffic loading are reviewed. A wide range of statistical/probabilistic approaches have been applied to the problem, using different quantities of data, with no clear 'winner'

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emerging. Two Extreme Value examples are used here as benchmark tests, against which a range of approaches are compared. The first example is the problem of finding the maximum of numerous normally distributed random variables, a problem for which the exact theoretical solution is known. The nature of the problem is studied using a number of samples with different quantities of data.

The second example is based on a carefully calibrated traffic load simulation model. The simulation is run for 5000 years so that, while the exact solution is unknown, it can be estimated very well and there is a high degree of confidence in the lifetime maximum results. As for the first example, several methods of prediction, using modest quantities of data, are tested to demonstrate the importance of the quantity of data in probabilistic assessments.

In this study no allowance for growth in traffic loads is made. Vehicle traffic is a non-stationary phenomenon with variation in both vehicle proportions and weights experienced over time as a function of economic, legal and technological developments. Despite the recent economic downturn, the European Commission [38] predicts a sustainable annual growth in road freight volume of between 1.5% and 2% per annum until 2030. O'Connor et al. [83] note a substantial increase in the number of 5-axle vehicles over a 10 year period. Sivakumar et al. [94] recognise the need to allow for growth in truck weights and traffic intensities and propose an economic projection analysis. OBrien et al. [76] consider growth in the numbers of heavy vehicles and provide a means of addressing the non-stationary nature of growing traffic. However, growth is considered to be beyond the scope of this paper.

2. Review of literature

Load effects (LE's) – bending moments, shear forces, etc. – result from traffic passing over a bridge. The process varies in time with many periods of zero LE when there is no traffic on the bridge and peaks corresponding to heavy vehicle crossings or more complex vehicle meeting or overtaking scenarios. The majority of the local peaks in LE are due to cars which are relatively light and there have been many efforts to simplify the problem by excluding consideration of these data. The methods of statistical inference used in the literature to predict the extremes of traffic LE's are quite diverse.

2.1. Tail fitting

In the context of this problem, many approaches fit a distribution to the tail of the cumulative distribution function (CDF) of the LE's. This can be justified by the fact that the distribution is often made up of a mixture of load effect types – for example, LE's due to 2-axle trucks and those due to heavy low-loader vehicles. For bridge traffic loading, the heavier vehicles tend to dominate, with the lighter ones making very little contribution to the probability of exceedance at the extremes. The tail can be chosen by engineering judgement when the cumulative distribution is seen to change at a particular probability level. Alternatively, some authors have fitted to the top $2\sqrt{n}$ of a distribution of n data, based on theoretical considerations [21]. Others have fitted to the top 30% of data [36] based on sensitivity analyses.

Two of the tail fitting approaches are particularly popular – Peaks-Over-Threshold (POT) and Block Maximum. POT considers the extent by which the peaks of LE exceed a specified threshold. The POT LE's are fitted to a probability distribution such as the Generalised Pareto distribution. In the Block Maximum approach, only the maximum LE's in given blocks of time (days, years, etc.), are considered. This has the advantage of time referencing the data which is necessary when calculating lifetime maximum probabilities of exceedance. Block maximum LE's can be fitted to one of a range of distribution types such as Generalised Extreme Value (GEV) (incorporating Gumbel, Weibull and Fréchet), or Normal. Fitting block maximum values to GEV and Normal distributions will be considered here.

The Block Maximum approach has the disadvantage that only one LE in each block of time is considered, even if several very large LE's are recorded. The POT approach addresses this issue but the selection of the threshold, below which LE's are discarded, is subjective. The Box–Cox approach is more general and aims to address the disadvantages of both POT and GEV. The Rice formula is also investigated as it was used for the extrapolations in the background study supporting the development of the Eurocode for traffic loading on bridges. However, while the Rice formula is a fitting to tail data, it is applied to a histogram of 'upcrossings' past a threshold, not to a CDF, and assumes a normally distributed process.

2.2. Full distribution fitting

Bayesian Updating is another approach that can be applied to bridge traffic loading. A probability distribution is assumed for the block maximum LE's and is updated using available LE data. While only tail data could be used, in this work, the Bayesian approach is used to update the entire distribution, not just the tail. Predictive Likelihood also seeks to develop a probability distribution for all LE's but uses a frequentist likelihood approach, assigning likelihoods on the basis of the quality of the fit to the measured data.

2.2.1. Peaks Over Threshold (POT)

Block Maximum approaches use only the maximum LE in each block of time. There is therefore a risk that some important data is discarded: if two unrelated extreme loading events occur in the same block of time, only one of the resulting LE's is retained. In such a case, the POT approach would retain both LE's as valid data.

To find characteristic maximum values of LE, data above the threshold must be fitted to a probability distribution. Coles [22] provides a brief outline proof that the Generalised Pareto (GP) distribution approximates the CDF of such POT data well. Crespo-Minguillón and Casas [31] use the GP distribution to model the excesses of weekly maximum traffic LE's over a threshold. James [56] applies the POT method to analyse load effects on railway bridges. Gindy and Nassif [47] analyse load effects caused by combined data from over 33 Weigh-in-Motion sites over an 11-year measurement period, and compare extreme values as predicted by both GP and GEV distributions.

A significant drawback of the POT approach is the issue of selecting the threshold. There are many different kinds of loading scenario on a typical bridge. For example, there are usually many single-vehicle crossings of standard 5-axle trucks. The probability distribution of LE's due to such an event type may be quite different from that due to large cranes or that due to 2-truck meeting events [15]. If the threshold is too low, there may be an excessive mixing of extreme event types with other less critical types which can result in convergence to an incorrect characteristic LE. On the other hand, if the threshold is too high, there will be too few peaks above the threshold, leading to high variance and unreliable results.

The basic principle in selecting a threshold is to adopt as low a threshold as possible, while maintaining a consistent trend in the data. The issue of threshold choice is analogous to the choice of block size in the block maxima approach, implying a balance between bias and variance. Two methods are available [22]: one is an exploratory technique carried out prior to model estimation; the other is an assessment of the stability of parameter estimates, based on the fitting of models across a range of different thresh-