Traffic load 'fingerprinting' of bridges for assessment purposes

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Synopsis
The paper describes a field trial of the use of a simple statistical 'extrapolation' technique for the determination of design load effects in existing bridges. Deflections were measured directly using lasers in the Foyle Bridge, and data were recorded for 155 daily 48-min samples. As only traffic load effects were of interest, wind-influenced deflections were removed by Fast Fourier transform analysis and temperature-induced deflections were removed through identification of traffic-free periods. A simple linear regression analysis using probability paper has been employed to determine the parameters which characterise the statistical distribution. The cumulative distribution function was then used to estimate the level of deflection with a 1000-year return period. Empirically derived formulas have been utilised to determine the variability in the 1000-year estimates and to calculate a design deflection which allows for this.

Notation
N is the no. of daily maxima in sample
a is the parameter of extreme value distribution
\( \alpha \) is the parameter of extreme value distribution
B is the safety index
\( \delta_{\text{def}} \) is the design value for deflection
\( \delta_{\text{1000}} \) is the deflection with 1000-year return period

\( p \) is the factor defined by eqn. (6)
\( \sigma \) is the standard deviation of daily maximum deflections
\( \sigma(\delta_{\text{1000}}) \) is the standard deviation of estimates of 1000-year deflection

Introduction
In recent years there have been significant improvements in the technology of weighing trucks while they are travelling at full highway speed. Results from weigh-in-motion (WIM) systems have been used for pavement design and research purposes and also for the determination of the normal (HA equivalent) bridge design load for the Eurocode, EC1. Following the method used for the derivation of the Eurocode normal loading, it is possible to load fingerprint an existing bridge for the purpose of assessment, i.e. to determine a design load specific to its particular location. In many instances, this may be significantly below the national bridge assessment loading, particularly if the bridge is located in a region of low industrial activity.

Bridge load assessment can be done either by collecting truck weight statistics using a WIM system and processing the results to determine a design load or by collecting the load effect (strain, deflection, etc.) statistics directly and processing these to obtain design values. Truck weight statistics can be determined using any of a range of commercially available WIM systems. Many of these use sensors embedded in the pavement such as piezo-ceramic cables, capacitative strips or bending plates. A comparative study of commercially available systems, for both accuracy and durability,

Fig 1. General arrangement of the Foyle Bridge
is in progress in Zürich, for which preliminary results have been published. An alternative WIM system, consisting of the use of a bridge or culvert as weighing scales, is also widely used. The process by which the Eurocode design load is determined from the truck weight statistics has been described and software has been developed.

When assessing the traffic load on a given bridge, both free-flowing and traffic jam conditions need to be considered. Free-flowing conditions tend to govern the design of short-span bridges while traffic jams, especially when frequent, tend to govern the design of longer bridges. When jams are rare, design load effects can be determined by collecting weight statistics using a WIM system and simulating traffic jams numerically. When jams are frequent or when free-flowing traffic conditions are being considered, direct measurement of load effects and statistical ‘extrapolation’ to determine design values can be more convenient. This method has advantages of simplicity and is especially useful when particular load-induced cracks or deflections are of concern.

In Northern Ireland the Foyle Bridge has been used experimentally for direct measurement of deflection statistics in free-flowing traffic and statistical ‘extrapolation’ to calculate site-specific design values. This was done as a field trial of the concept which would normally be applied to a bridge being considered for repair or replacement. It also serves as a baseline study should deflection in the bridge increase in the future because of changes in freight transport trends in the area. Traffic jam situations were not considered in this field trial.

The Foyle Bridge

The Foyle Bridge carries the A2 trunk road across the River Foyle about 3km downstream from the centre of the city of Londonderry. The overall layout is shown in Fig. 1. The structure is 866m long and comprises three main spans in steel, totalling 522m, together with a 344m approach viaduct in prestressed concrete. Full details of the structure have been published elsewhere by Prescott et al., Wex et al., Quinm and Hunter & McKeown.

The bridge consists of two independent parallel structures, each carrying a single carriageway. The main steel structure consists of twin steel box girders which vary in depth from 3m at midspan to 9m over the intermediate supports. The structure is restrained against horizontal movement at the west abutment, and there are expansion joints at the junction of the steel and concrete sections. Rotational bearings are provided at the top of the intermediate piers, horizontal movements being accommodated by flexing of the piers.

The bridge carries much of the local city traffic between the two sides of the river but is also the primary trunk route between North Donegal and Northern Ireland. It was, therefore, designed to carry the full highway loading specified for trunk roads at the time of its design (1980). However, as it serves a primarily rural area, the frequency of heavy loads is very much less than would be the case in a heavily industrialised region where a large proportion of lorries may be expected to be near the maximum legal weight.

For several years the steel portion of the bridge has been the subject of ongoing monitoring. A computer controlled remote access monitoring system has been installed which allows a range of stresses, deflections, temperatures and wind parameters to be observed. The equipment includes a deflection measuring system which is shown diagrammatically in Fig. 2. In each box, two lasers have been fixed at midspan and each projects a spot of light onto target fixed over an intermediate support. Any movement of the lasers causes the position of the light spots to vary, and this movement is tracked by computer controlled cameras. The resulting apparent movements are then combined to give the translational and rotational movements of the midspan position. Full details will be found in refs. 17 and 18. Measurements have been recorded at a rate of 8.3Hz with typical scans consisting of 4096 readings taken over a period of about 8 min. Data taken intermittently over a 6 month period were used for the statistical analysis. Six 4 hour scanning periods were used to represent all parts of each 24 hour day. One 8 min scan was taken during each of these periods, giving a total scanning period/day of 48 min. Data fitting these criteria were identified for 157 days in the 6 month period. As the percentage of non-working days (weekends and holidays) in Northern Ireland is 30%, data for 2 working days were discarded at random to leave 109 working and 46 non-working days.

Processing of Foyle Bridge data

The observed movements of the bridge deck consisted of four distinct components: static deflections due to traffic loads, vibration due to the impact loading of the traffic, oscillation induced by the wind, and movements due to temperature changes. It was necessary, therefore, to process the raw data to separate the various components isolating the deflections due to (equivalent static) traffic loads.

Removal of natural frequency vibrations

Vibrations, whether induced by traffic or wind, are most likely to occur close to the natural frequencies of the structure, with the largest amplitude being at the first natural frequency which, in this case, was 0.42Hz. A digital filter with the response characteristic shown in Fig 3 was devised. When this filter was applied to the data, signals with a frequency of less than 0.1Hz passed through unchanged while those at or near the natural frequency of the structure were reduced by approximately 98%. As a signal frequency of 0.1Hz corresponds to the trace produced by a vehicle crossing the bridge at 37m/s (84mph), the filter leaves the static traffic effects unaffected while removing almost all the vibrational effects. The effect of applying the filter to a typical scan is shown in Fig 4. The resulting output shows the effect of
several vehicles of different weights crossing the bridge during the scan period.

Removal of temperature effects
In addition to vibrations, there are significant deflections induced in the Foyle Bridge by daily thermal fluctuations. Thermal expansion of the deck is resisted by bending of the piers. As these are pinned to the deck at a point significantly below the neutral axis, expansion induces a concentrated moment in the deck which generates bending, and, hence, vertical deflection. The result is temperature-related deflections significantly greater than those generated by differential temperature strain variations through the depth of the deck. Some temperatures were monitored in the Foyle Bridge. However, an accurate prediction of resulting deflections would require detailed temperature distributions and analysis of the non-prismatic bridge. Temperature did not generally change significantly during the 8 min duration of a typical scan, making an alternative approach for the removal of thermal effects possible. This consisted of establishing a baseline deflection for each 8 min scanning period. Changes between scans in the baseline deflection were taken to be generated by thermal movements while variations from the baseline were taken to be induced by traffic loading. However, this baseline cannot be a simple mean of all deflections recorded over the period as the mean is increased by heavier and more frequent traffic. The baseline was therefore taken as the mean deflection during periods when no (significant) traffic was present on the bridge.

A typical plot of deflections (after removal of natural frequency vibrations) is illustrated in Fig 5. The passing of individual vehicles can be identified in the figure by a characteristic shape similar to the influence line of Fig 6. Periods when no significant traffic was present were identified through comparison of successive local minima and maxima in the plot. When a local maximum followed a local minimum and the difference was less than 10mm, the variation between them was deemed to be minor and the values were deemed to belong to the baseline. However, if the difference between successive extremes exceeded 10mm, a vehicle of significant weight was assumed to be present and these deflections were not used for the calculation of the baseline deflection. The extremes used in the calculation of the baseline are shown in Fig 5 (open circles) for a typical example. This method would result in an inaccurate baseline in the event of a very slow-moving heavy vehicle being present. However, the probability of significant inaccuracy is felt by the authors to be acceptably low.

Statistical analysis
The deflection induced by a passing vehicle on the bridge is clearly a random variable with a mean and a standard deviation. However, when calculating design values, it is useful to consider a different random variable, i.e. the maximum deflection in a specified period. For the Foyle Bridge the maximum deflection from the 48 min daily sample was the random variable considered. A random variable such as this, which is the maximum of a number of other random variables, often conforms to the extreme value type-I statistical distribution. In statistics the cumulative distribution function (CDF) is the probability of the random variable being less than a specified value. For the extreme value type I distribution, the CDF is given by:

\[ P(\delta < \delta) = \exp[-\exp(-\gamma)] \]

where

\[ y = \alpha (\delta - \mu) \]

and where \( \alpha \) and \( \mu \) are parameters that characterise the distribution (analogous to mean and standard deviation for other distributions). A convenient test for conformity to this probability distribution was employed, consisting of plotting sample values on probability paper. The process consisted of ranking the daily maxima in ascending order and calculating a plotting position for each point. Goda has suggested a plotting position of:

\[ \text{plotting position} = i - 0.44 \]

\[ N + 0.12 \]

where \( i \) is the rank ( \( i = 1 \) corresponds to smallest of the maxima) and \( N \) is the number of data points. Each daily maximum was plotted as the ordinate while the inverse CDF of the corresponding plotting positions was plotted as the abscissa. The plot for maximum daily deflections, illustrated in Fig 7, is substantially linear, verifying that this random variable complies well with the extreme value type I distribution.
The parameters which characterise this statistical distribution, \( \alpha \) and \( \alpha \), are the intercept and the reciprocal of the slope, respectively, of the line of Fig 7 and can be calculated by linear regression on this graph. The parameter values, having been calculated, the design value of a load effect for a specified return period is readily calculated. For a 1000 year return period (as recommended for design purposes in EC2) there are \( 10.96 \times 10^8 \) samples, which corresponds to a probability of \( 1/10.96 \times 10^8 = 91.26 \times 10^{-9} \). Equating the CDF of eqn. (1) to a probability of \( 1/10.00 \times 10^8 \), and substituting for \( y \) in eqn. (2) gives a formula for the 1000-year deflection:

\[
\delta_{1000} = \frac{\gamma_{1000}}{\alpha} \tag{3}
\]

where

\[
\gamma_{1000} = -\frac{\ln(\ln(1 - 91.26 \times 10^{-9}))}{16.21} \tag{4}
\]

The accuracy of the 1000-year deflection given by eqn. (3) clearly depends on the quantity of data used for its calculation. Goda\(^{a}\) gives empirical formulas which can be used to establish a margin of error to allow for variability in the result. The standard deviation of the estimate of 1000-year deflection is:

\[
\sigma(\delta_{1000}) = \rho \delta_0 \tag{5}
\]

where \( \delta_0 \) is the standard deviation of the daily maximum deflections and:

\[
\rho = \sqrt{\frac{1 + 0.64 y_{1000}^2 \exp(9N^{1.1})}{N}} \tag{6}
\]

The design deflection allowing for estimation error then becomes:

\[
\delta_{\text{des}} = \delta_{1000} - \beta \sigma(\delta_{1000}) \tag{7}
\]

where \( \beta \) is a safety index whose value depends on the degree of reliability required.

**Results**

Samples from the 155 daily maximum deflections were used to calculate design deflections for the Foyle Bridge. Samples ranging in size from 7 to 155 days were used for the calculation of the design deflection. In each case the unbiased sample standard deviation, \( \sigma \), was found and linear regression formulas were used to determine the slope and intercept of the line on probability paper. The 1000-year deflection was estimated from eqns. (3) and (4) and the standard deviation of the result was determined from eqns. (5) and (6). A unit value for \( \beta \) was used in eqn. (7) for this example. The results are presented in Table 1 and Fig 8. It can be seen that calculations of the 1000-year deflections based on the first 7 and first 28 days of data were similar and larger, respectively, than later estimates using more data. This was because there were few large deflections in the first 7 days and there were many quite large deflections in the subsequent 21 days. Daily maxima in the first 7 days were clustered, resulting in a smaller than typical sample standard deviation. However, the \( \beta \)-factor, reflecting the small number of days used in the sample, is quite high, resulting in a high total variability in the estimate of the 1000-year deflection. Daily maxima in the first 28 days are high and variable. The result is a high estimate of the 1000-year deflection and a high estimate of variability in the result. When results from 56 and more 48 min daily samples are used, the design deflection is significantly reduced, and a marked convergence is apparent in Fig 8.

**Conclusions**

The feasibility of traffic load fingerprinting for highway bridges is demonstrated using the load effect of deflection in the Foyle Bridge. Techniques suitable for non-specialists in statistics are presented for the verification of compliance with the extreme value type I statistical distribution and the calculation of the distribution parameters. Formulas are presented for the calculation of expected variation in the predictions and of an appropriate design value for the load effect. Results demonstrate effective isolation of the traffic-induced load effect and illustrate a convergence in the design deflection with an increasing number of data samples.

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