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Considering Traffic Growth in Characteristic Bridge Load Effect Calculations

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ABSTRACT: Traffic volumes and weights increase with time. This is an important consideration in order to accurately calculate characteristic load effects for the design and assessment of bridges. A modeling approach is presented which can allow for future growth of truck weights and volumes when assessing truck loading on bridges. Weigh-in-motion data from a site in the Netherlands is used as an example to demonstrate traffic growth at that site. In assessing the effect of growth on characteristic load effects, different growth rates for both truck volumes and truck weights are considered. It is found that growth of truck weights has considerably more influence although growth in truck volumes also has a significant effect.

1 INTRODUCTION

Characteristic bridge traffic load effects are used in the design and assessment of bridges. The more accurate these estimates, the more efficient the design or assessment. Accurate design can eliminate the need for future strengthening and at the assessment stage, accurate estimates of loading may result in a questionable bridge being saved rather than replaced.

Idealised load models are generally used to represent traffic loading in the design/assessment of bridges (EC1 2009; Highways Agency 2011; AASHTO 2012). This is often an overly conservative approach as these models must be appropriate for all bridges, including the most heavily trafficked structures. The most accurate method for estimating site-specific characteristic load effects is to use weigh-in-motion (WIM) data. This involves weighing the axles of normal traffic as it passes along a road at a regular highway speed (COST323 2002).

To calculate the required characteristic load effects (e.g. 1000-year return period values) from WIM data, the measured traffic is first passed over the relevant influence line to obtain the 'observed' load effects. The characteristic load effects can then be calculated by extrapolating from the observed values. There are a number of approaches to this. Statistical extrapolation is probably the most common and has been used by many authors. Nowak (1993) plotted the observed data on Normal probability paper and extrapolated using a Normal distribution. Extrapolation using a generalised extreme

value (GEV) distribution has since become popular (Getachew & OBrien 2007; Miao & Chan 2002; Caprani 2012). A number of other extrapolation techniques have also been used and the accuracy of different approaches has been compared by OBrien et al. (2015).

Although extrapolation techniques are effective for calculating characteristic load effects, there is a risk that the approach is not considering certain types of truck loading events that have not been measured during the WIM measurement period. In order to generate new trucks and new types of loading events, long run Monte Carlo type traffic simulations can be used (Nowak & Szerszen 1998; Enright & OBrien 2013; Bailey & Bez 1999). This involves fitting suitable distributions to the various measured parameters – axle weights, axle spacings, inter-vehicle gaps, traffic flow rates, etc. Characteristic values can then be extrapolated from a number of years of simulated traffic, or long-run simulations representing thousands of years of traffic can be used to avoid the need for extrapolation (Enright & OBrien 2013).

The extrapolation techniques discussed above generally assume that the measured traffic conditions will prevail throughout the service life of the bridge. However, traffic is growing with time. Road freight transport in the European Union is expected to grow by about 1.8% until 2030 due to economic growth and an increased flow of freight traffic between member states (Capros et al. 2008). This is likely to result in an increase in both the weight and frequency of trucks. This growth must be considered in order to obtain characteristic load effects that are relevant throughout the service life of the bridge.

OBrien et al. (2014) developed a method for considering traffic growth in load effect calculations. However, the method considers growth in truck volumes but growth in truck weights is not allowed for. This paper proposes a method to model growth of both truck weights and volumes. The approach is applied using Netherlands WIM data. Different levels of growth are examined for both weights and volumes and the effect of each type of growth is compared. This is useful information for road owners who might be considering increasing legal weight limits.

This work was performed as part of the CEDR Re-Gen project (Leahy et al. 2015) and further information can be found at www.re-gen.net.

2 WIM DATA

The WIM data used in this study was collected between February and June 2005 on the A12 near Woerden in the Netherlands. This data was used as it contained two-lane same-direction traffic with time stamp records to an accuracy of one hundredth of a second for each vehicle. This time stamp accuracy is required in order to accurately determine the exact relative location of trucks on the bridge (Žnidarič et al. 2015).

It should be noted that there is very heavy loading at this site. It has a large average flow rate of 6600 trucks per day and recent studies, which compared this site to other sites in Europe, showed the loading to be significantly greater than at the other European locations (OBrien & Enright 2012; Enright & OBrien 2013). As a result the characteristic load effects calculated for this site will not be typical of sites across Europe. However, it is believed that the increases in load effects with traffic growth should be comparable with other sites.

All WIM databases contain a certain amount of erroneous data. This data must be identified and removed before any meaningful analysis can be performed. Erroneous data can be as a result of different factors. It can be as a result gross errors while weighing certain individual truck or it can also be as a result of calibration drift or loss of calibration of the system which affects all records over a certain period. The cause of individual errors is not always known but can sometimes be caused by a vehicle straddling two lanes or by a long vehicle being recorded as two separate vehicles. Rules similar to those proposed by Enright and OBrien (2011) are used here to filter erroneous records

Once the erroneous records have been removed, the remaining truck records are then filtered to remove permit trucks. Permit trucks are removed from the WIM analysis as permits trucks are covered by Load Model 3 (EC1 2009) which is outside the

scope of this work. These trucks are removed using filtering rules proposed by Enright et al. (2015).

In addition, the database includes weekends and bank holiday traffic which is significantly lighter in volume and average Gross Vehicle Weight (GVW), in comparison to normal weekday traffic. Due to these different statistical properties, the weekend and bank holiday data is removed so the analysis can be applied to a homogeneous dataset.

3 METHODOLOGY

3.1 Traffic simulation model

A Scenario Modelling approach (OBrien & Enright 2011; Leahy 2013) is used to perform long run traffic simulations of two-lane same-direction traffic. With two-lane same-direction traffic, there are many important correlations between truck weights and inter-truck spacing which influence the results. These correlations must be considered in order to accurately simulate the traffic. With the Scenario Modelling approach, the measured traffic from the WIM data is perturbed to create new traffic. The modelling approach is concerned only with the trucks in the WIM data; the cars are ignored as they are considered insignificant for loading on the bridge lengths considered here (15 – 40 m).

The measured data is divided into a series of scenarios which are then randomly selected and joined together to simulate a stream of traffic. During this process the selected scenarios are perturbed using a smoothed bootstrap approach to generate new traffic (OBrien & Enright 2011). This approach varies the GVW, the in-lane gaps and the inter-lane headway – see Figure 1.

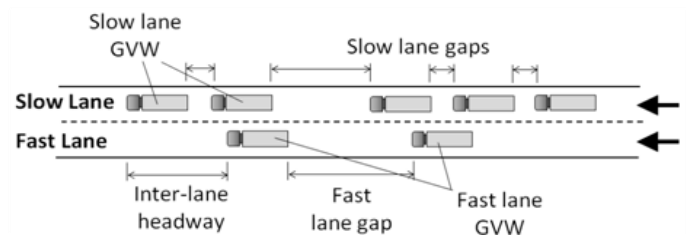


Figure 1. Sample scenario showing the properties which are varied in Scenario Modelling.

A 40 year simulation of traffic at the Netherlands WIM site is shown in Figure 2 with no traffic growth. The simulated maximum daily load effects for midspan bending moment on a 15 m bridge are plotted alongside those of the measured WIM data. It can be seen that the simulated load effects are a good fit to those of the WIM data and that the trend in the measured data is effectively extrapolated beyond the measured data.

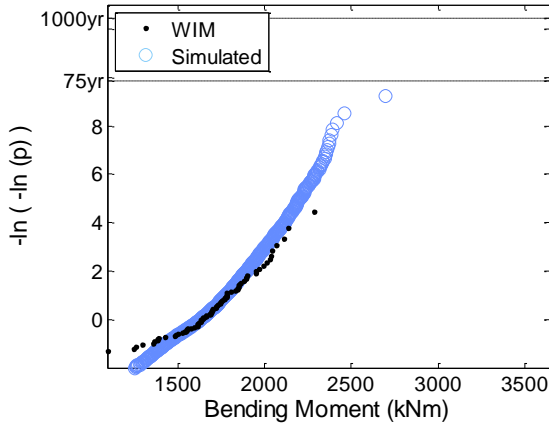


Figure 2. Maximum daily midspan bending on a 15 m bridge for a 40 year traffic simulation with the corresponding values from the WIM data.

3.2 Modelling traffic growth

Increased freight transport can be divided into both a growth in flow and growth in the weights of trucks. As noted previously, an annual growth rate of 1.8% until 2030 has been predicted by the European Commission. This growth is likely to result in increases in both the frequency and weight of trucks. However, it is not known what proportion of each parameter will contribute to the total growth. As a result, a number of different growth rates and combinations of growth rates are examined for the flow and weight of trucks – see Table 1.

Table 1. Growth Rates Examined.

| | | Annual Flow Growth | | |
|--------|------|--------------------|----|----|
| | | 0% | 1% | 2% |
| Annual | 0% | ✓ ¹ | ✓ | ✓ |
| Weight | 0.5% | ✓ | ✓ | ✓ |
| Growth | 1.0% | ✓ | ✓ | ✓ |

¹ The reference dataset with which the cases with growth will be compared.

The increase in flow is modelled by assessing each hour of the day independently. This is done to preserve the variations in flow by time of day. This variation can be seen in Figure 3. Increased flow with time is modelled by first determining the flow associated with the hour of the day and the year being simulated. Scenarios are then randomly selected from scenarios with this flow rate. This results in a gradual increase in flow rate over the simulation period. The measured hourly flow is illustrated in Figure 3 along with the flow rate at the end of a 40-year simulation period with an annual traffic growth rate in flow of 2%.

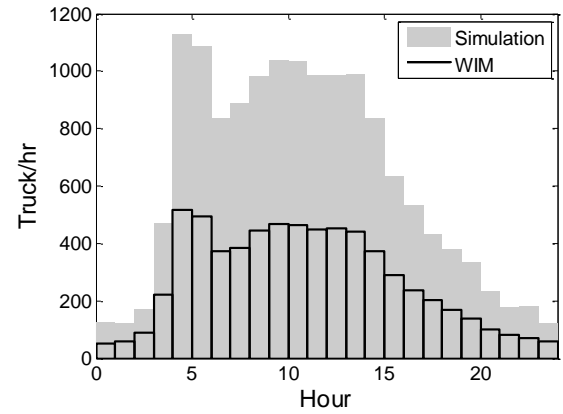


Figure 3. Flow variation at the WIM site and simulated flow rates at the end of 40 year simulation period with 2% yearly flow growth.

Increases in the weight of trucks with time are also modelled. To realistically increase truck weights, the axle configurations must also change as it is not realistic as axle configurations are largely dependent on the load capacity, and hence weight, of the truck. To increase truck weights, the measured traffic is separated into two tonne weight bands – see Figure 4. For each weight band we have a distribution for the number of axles, with examples shown in Figure 5. It can be seen as the weight of the truck increases, the distribution for the number of axles changes. To increase the weight of a truck in a scenario, it is replaced with another truck randomly selected from the appropriate higher weight band. In general, the new truck will be expected to have the same or more axles than the truck it replaced.

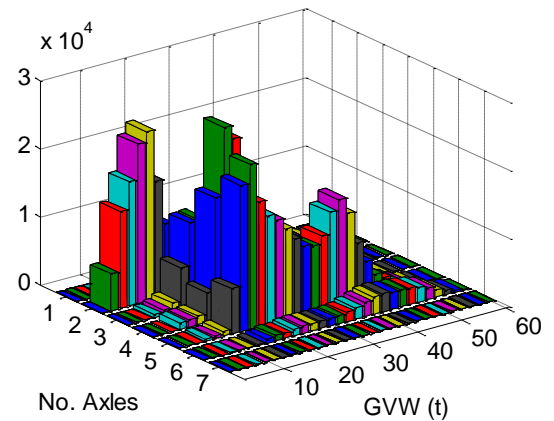


Figure 4. 3D histogram with the number of axles on the trucks in 2 t weight bands.

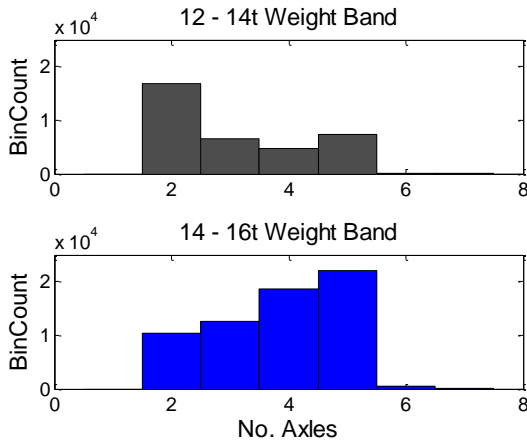


Figure 5. Histogram of the number of axles in the 14-16 t and 16-18 t weight bands.

In the simulation, measured trucks can only be replaced by heavier trucks from the WIM data up to a certain weight limit. Above a certain threshold there will not be any heavier trucks in the WIM data to randomly select to replace the measured truck – see right hand tail of Figure 6. This is particularly relevant towards the end of the simulation period when large increases in truck weight may need to be simulated. As a result, it was decided that the random selection process for simulating heavier trucks would only be applied to trucks with a measured GVW of less than 50 t. This ensures that there is always a selection of heavier trucks to randomly select. Above 50 t, the original axle configuration is kept and the weights on the axles are increased to simulate growth in weights. However, it is not realistic to continue to increase the weight on an axle without imposing an upper limit. After examination of the trends in axle weights in the WIM data it was decided to impose an upper limit of 20 t above which the axle weights could not be increased. It should be noted that there were a small number of measured axles which exceeded 20 t and these were allowed to remain in the data.

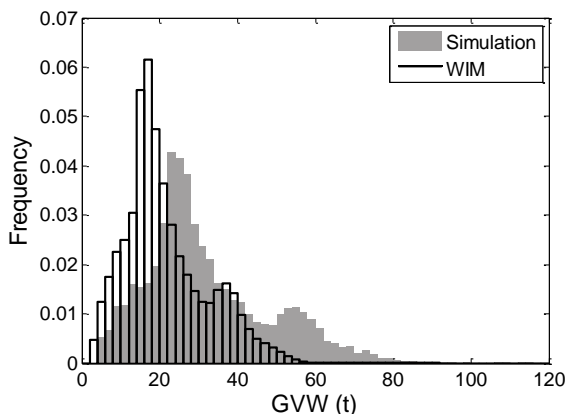


Figure 6. GVW histograms for the WIM data and for the simulated traffic at the end of the 40-year simulation period with 1.0% yearly growth.

Figure 7 shows a 40 year simulation with the maximum growth rate examined (annual increases of 2.0 % in flow and 1.0 % in weights). When compared with the equivalent simulation with no growth in clear. Figure 2, the effect of traffic growth is clear.

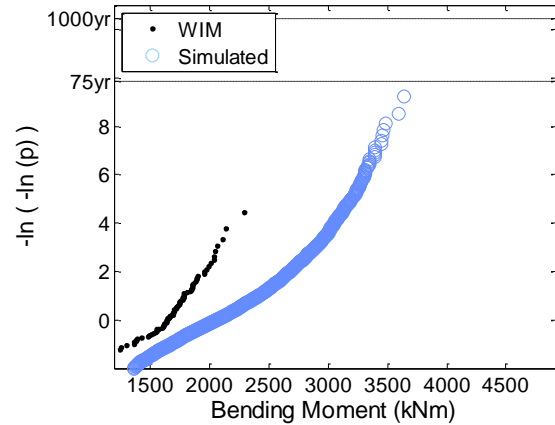


Figure 7. Maximum daily midspan bending on a 15m bridge for a 40-year traffic simulation with annual growth of 1% in weight and 2% in flow.

3.3 Influence line analysis

The simulated traffic is passed over influence lines to examine the following three load effects for bridge lengths of 15, 30 and 45 m:

- LE1: Midspan bending moment on a simply supported bridge.
- LE2: Shear at the support of a simply supported bridge.
- LE3: Negative bending moment over the central support of a two span continuous bridge.

When calculating load effects in two-lane same-direction traffic, each lane is analysed using a simple influence line. The transverse stiffness of the bridge is allowed for by using lane factors [6]. The primary lane contributes all of its calculated load effect whereas the contribution of the secondary lane is multiplied by a lane factor. The lane factors used are shown in Table 2 and are those which were found by Enright & O'Brien (2013) to represent stiff bridges where there is relatively large transverse distribution of load.

Table 2. Lane Factors for overtaking lane with high transverse stiffness.

| Load Effect | Lane Factor |
|--|-------------|
| LE1: Mid-span bending moment, simply supported | 1.0 |
| LE2: Support shear, simply supported | 0.45 |
| LE3: Central support hogging moment, 2-span continuous | 1.0 |

3.4 Non-stationary GEV method for estimating characteristic load effects

To account for traffic growth, OBrien et al. (2014) proposed the non-stationary GEV approach for estimating characteristic load effects. With this method, the parameters of the distribution are time dependent which allows the distribution to increase with traffic growth – see Figure 8.

To calculate the characteristic load effects for a bridge at the WIM site, a 40-year traffic simulation is performed for each annual growth rate for weight and flow. 40 years represents the remaining service life being assessed. The non-stationary GEV distribution is then fitted to the maximum 25-day load effects using maximum likelihood estimation. The 1000-year return period load effect can then be calculated. It is important to differentiate between the service life and return period. Service life is the period over which the traffic growth is occurring while return period is a level of safety.

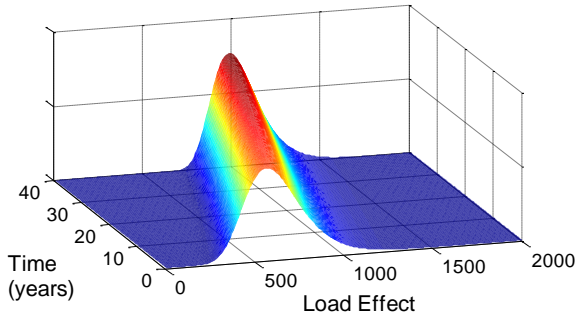
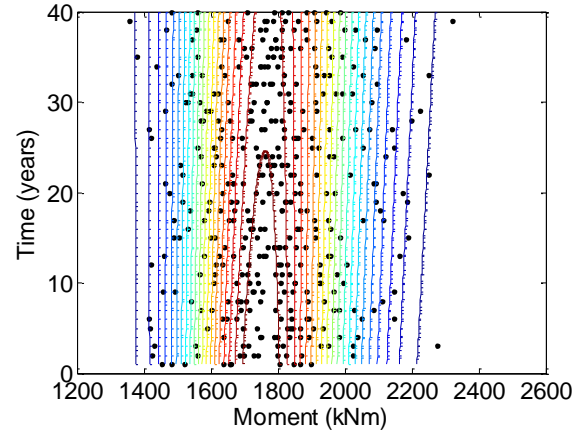
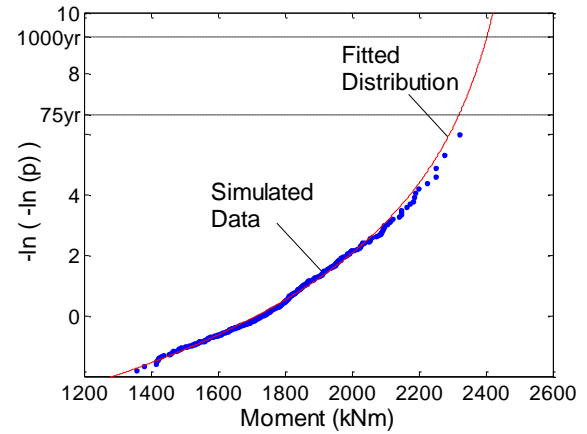


Figure 8. Non-stationary GEV distribution.

Figure 9 (a) shows the simulated maximum 25-day load effects increasing with time and a contour plot of the fitted non-stationary GEV distribution. Figure 9 (b) shows a Gumbel probability paper plot of the same data and the fitted distribution. The plot is effectively a cumulative distribution function (CDF) with the y-axis values plotted on a double log scale to allow the tail of the distribution to be easily examined. It shows that the fitted distribution is a good fit to the measured data and is effective in extrapolating the trend in the measured. It should be noted that Figure 9 plots the maximum 25-day load effects used in the analysis, unlike Figure 2 which shows maximum daily load effects.



(a) Simulated data with contour plot of fitted distribution.



(b) Probability paper plot.

Figure 9. Non-stationary GEV distribution fitted to 25-day maximum load effects for a IL3 on a 30 m bridge for a 40 year simulation with 1% flow and 1% weight growth.

A 1000-year return period was used to calculate the characteristic load effects for the calibration of the Eurocode LM1. This is predominantly used for the design of new bridges. For the assessment of existing bridges, the remaining service life is generally less than the design life and it may be more appropriate use a shorter return period, i.e., a lower level of safety. The 75-year return period is shown on some of the plots as an example of a smaller return period. A return period of 75 years is used in bridge design in the United States but a smaller return period can be used for assessment (Minervino et al. 2003).

4 RESULTS

Table 3 shows the increase in characteristic load effect for the simulation with maximum annual growth (2.0% flow growth and 1.0% weight growth) in comparison to the results with no growth. This produced an average increase of 48% with a maximum increase of 64% occurring for hogging moment on a 45 m bridge. Hogging moment appears to be the most sensitive of the load effects to traffic growth.

Table 3. Percentage increase in α -factor with 2% flow + 1% weight annual traffic growth.

| Bridge Length (m) | IL 1 | IL 2 | IL 3 |
|-------------------|------|------|------|
| 15 | 36 | 45 | n/a |
| 30 | 44 | 49 | 52 |
| 45 | 46 | 49 | 64 |

It can also be seen that greater increases are evident for the longer bridge lengths. This is likely due to multiple truck presence events being more critical on longer spans. Increases in flow will have more influence on these events than on the single truck loading events which tend to govern for short bridge lengths.

Shear at the support (IL2), varies less than the other load effects with bridge length. IL2 has a lower lane factor as only a small proportion of the load in one lane causes shear at the support of the adjacent lane. The critical event in that case is more likely caused by a single truck loading event rather than side-by-side events. As a result shear may be more dependent on individual axle weights rather than growth in overall vehicle weight. As axle weights were not allowed to increase above 20 t during simulation, there is an upper limit to axle weights but not to gross weight. This could explain the reduced influence of growth on shear (IL2).

Table 4 shows the average increase in characteristic load effect across all influence lines examined for each combinations of growth rate examined.

Table 4. Average increase in characteristic load effect for each combination of growth.

| | | Annual Flow Growth | | |
|--------|------|--------------------|-----|-----|
| | | 0% | 1% | 2% |
| Annual | 0% | - | 6% | 9% |
| Weight | 0.5% | 19% | 27% | 31% |
| Growth | 1% | 43% | 51% | 48% |

It should be noted that there is a certain degree of random variation in simulations such as these which are based on random number generation. This is apparent in Table 4 with the results for an annual weight growth rate of 1%, where the result for 1% growth in flow (51%) is greater than for 2% growth in flow (48%).

5 CONCLUSIONS

As freight traffic is expected to grow significantly until at least 2030, traffic growth needs to be allowed for when modelling traffic loading on bridges. A scenario modelling traffic simulation approach is used to model growth in truck weights and volumes

in data measured at a Netherlands WIM site. A time-varying GEV distribution is fitted to the simulation results in order to determine characteristic load effects. Different traffic growth rates are assumed over a 40-year service life.

The results show that growth significantly affects characteristic load effects for all bridge lengths and influence lines examined. Growth in weight has a much more significant effect than growth in flow, with a 1% annual growth in flow causing an average increase in characteristic load effects of 6% over the 40-year service life. In comparison, a 1% annual growth in truck weight results in an increase of 43%.

The results highlight the need to consider traffic growth when assessing site-specific traffic bridge loading. It also identifies the need for road owners to consider traffic growth when developing traffic load models for bridge design/assessment.

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