THE GOVERNING FORM OF TRAFFIC FOR HIGHWAY BRIDGE LOADING

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Abstract
Traffic loading is one of the most variable parameters in a bridge reliability assessment. Its accurate assessment potentially offers large savings due to reduced bridge rehabilitation or replacement costs. It is frequently assumed that free-flowing traffic (incorporating dynamic effects) governs for short- to medium-length bridges, whilst congestion governs for longer bridges. In this paper, for a range of bridge lengths and load effects, several traffic congestion models are considered, including the most common in the literature, as well as a model based upon traffic micro-simulation. For the critical model, the dynamic ratio that would be required for free-flowing traffic to govern is determined. For a range of bridge lengths, these dynamic ratios are larger than would be expected, and thus the authors conclude that contrary to the common assumption, the governing form of traffic may be congested traffic.

Keywords: Bridge, traffic, loading, microsimulation, congestion.

1. Introduction

The assessment of existing highway infrastructure is correctly viewed as an area in which significant potential for savings in repair and rehabilitation can be made. Since traffic loading is one of the most variable parameters in a bridge reliability assessment, its accurate estimation can have a significant impact on potential savings. Using measured traffic data, the load effect, or effects, on a particular bridge, or a range of bridges, can be estimated with confidence. Recent advances in the extrapolation of these load effects to the lifetime of the bridge structure also engender confidence in the lifetime load effect estimation.

1.1 Background

In the process of calculating load effect outlined above, an often-made assumption is that free-flowing traffic, allowing for dynamic effects, governs for spans below about 40 m, and congested traffic governs for spans above this. Free-flowing traffic may be critical because of the existence of both the static load of the vehicles and the extra load effect caused by bridge-truck dynamic interaction. In contrast, since congested traffic moves slowly, little dynamic interaction is observed. However, since more vehicles may be on the bridge due to the smaller gaps between vehicles, the static component of load effect will be greater than that of the free-flowing situation. Therefore, the governing form of traffic depends both upon the level of dynamic interaction and the density in which vehicles are present on the bridge. Recent advances (Gonzalez et al (2008) and Caprani (2005)) in the statistical analysis of dynamic interaction have shown that the dynamic increment may not be as high as once thought. This raises doubts about the governing form of traffic and is a critical issue, given that the vast majority of highway bridges are short- to medium-length bridges.

2. Bridge Traffic Load Simulation

2.1 Weigh-In-Motion Data

This work is based on data taken from the 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 and this results in conservative loading for a 2-lane bridge. Five days of traffic data was measured (an admittedly short duration), yielding 17 756 and 18 617 trucks in the north and south slow lanes respectively, giving an average daily truck flow of 6744 trucks. Only static weights were measured and thus the subsequent analyses neglect dynamic effects.

2.2 Modelling of Traffic Parameters

The traffic model required to simulate bridge load effects must be consistent with the measured traffic at the site it represents. Yet, it is important that there is variation from the measured traffic in the model; otherwise the model would only represent multiple sets of the same traffic. By using parametric statistical distributions, the traffic model may remain sympathetic to the measurements, yet retain the capacity to differ. The recorded WIM data was analysed for the statistical distributions of the traffic characteristics of the site for each lane. This modelling process is described by Caprani (2005). Of particular importance is the headway model (time gap between front of successive vehicles), which is modelled with a number of distributions dependent on flow, as described in OBrien and Caprani (2005).

2.3 Simulation of Bridge Traffic Loading

Monte Carlo simulation is used to generate traffic files that maintain the characteristics of the measured site. This is done so that the period of traffic data available for analysis is extended to a suitable length. The resultant traffic file is then used to calculate bridge traffic load effect.

A time-stepping algorithm is used to process the traffic file for bridge load effect. Cars are neglected in this algorithm. This is reasonable since they contribute little to bridge load effect, save for the effect they have on the spatial disposition of the trucks, and this will already have been accounted for in the traffic modelling. The trucks are moved across the influence lines of interest in 0.1 second intervals. Whilst it is acknowledged that this interval can mean some load effect maxima are not caught (for example shear forces), a sensitivity study showed 0.1 seconds to be a reasonable balance between speed of execution and accuracy, with maximum difference of under 5%. The maximum load effect that occurs any time between a truck on or off event is recorded along with its constituent trucks.

2.4 Statistical Analysis of Traffic Loading

Extreme value statistical theory is used in this work to analyse the load effect data obtained from the simulations, and to extrapolate to the design level of the structure. In particular the block maxima approach is used (Coles (2001)) and a period of one day is taken as the block size. Caprani et al (2008) demonstrate that bridge load effect is caused by a mixture of loading event types. For example, a load effect that results from 3-trucks does not have the same distribution as a load effect that results from 5-trucks. To mix such load effects is to violate the assumption of extreme value theory that the data must be independent and identically distributed. Caprani et al (2008) propose the Composite Distribution Statistics (CDS) model to solve this problem. The loading event data from the simulations is processed to obtain the daily maximum load effect value for each load event type and for each of the load effects and bridge lengths considered. The Generalized Extreme Value (GEV) distribution is used to model the daily maximum distribution of each loading event type:

$$G(x) = \exp\left\{-\left[1-\xi\left(\frac{x-\mu}{\sigma}\right)\right]_{+}^{1/\xi}\right\} \tag{1}$$

where μ, σ, ξ are the location, scale, and shape parameters respectively. The CDS distribution of daily maximum load effect, $G_C(\cdot)$, is then given by:

$$G_C(x) = \prod_{j=1}^{N} G_j(x) \tag{2}$$

In which N is the number of event types, $G_j(\cdot)$ is the GEV distribution of the *j*-truck loading event. The design load effect is then calculated numerically from this distribution as that corresponding to a 1000-year return period, as is used in the Eurocode (EC1.2 (2003)).

3. Traffic Models

In the present study, several forms of traffic models are considered. For the free-flow models, the measured hourly flow rate of trucks of the Auxerre site are maintained, thereby eliminating truck volume as a variable. Also, the site-measured truck composition is used.

3.1 Standard Free-Flow Model (SFFM)

Free-flow traffic models have been used for many years to model highway bridge loading (Caprani (2005)). Measured parameters such as speed and hourly flow rates can be maintained throughout a simulation. However, there remains the problem area of headway, or distance (in time) from the front of one truck to the front of the subsequent truck. In much previous work it is common to neglect cars and to only consider the headway between trucks (see Caprani (2005) for a fuller review; examples are Nowak and Hong (1991) and Vrouwenvelder and Waarts (1993)). Often the negative exponential distribution is used to model headway, but this is shown by OBrien and Caprani (2005) to be problematic since a minimum gap must be artificially imposed. These authors propose a model that is more sympathetic to the measured headway data, accounts for flow, and does not require subjective assessments of minimum gap. In the present study the headway model of OBrien and Caprani (2005) is used with measured site flow properties to constitute the standard free-flow model.

3.2 Standard Congestion Model (SCM)

Congested traffic modelling for loading on short- to medium-length bridges has not been studied extensively. Nowak and Hong (1991) modelled static configurations of traffic with assumed gaps of 15 ft (4.57 m) and 30 ft (9.14 m). Vrouwenvelder and Waarts (1993) use two models: for distributed lane loads a gap of 5.5 m is used, whilst for full modelling a variable gap of 4 to 10 m is used. In the background studies to the Eurocode (EC1.2 (2003)), Bruls et al (1996) and Flint and Jacob (1996) use a 5 m gap between vehicles.

In this study, the gap between vehicles is considered as a stochastic variable. Three normally distributed gaps are initially considered: 5, 10 and 15 m, each with a coefficient of variation of 5%. After some preliminary simulations and comparisons are made, the standard congestion model is taken to have the 5 m mean, due to its prevalence in the literature.

3.3 Traffic Microsimulation Model (MS-IDM)

Many of the problems associated with previous traffic modelling for bridge loading can be solved by using traffic microsimulation techniques. Such techniques model the actual driving behaviour of vehicles on the roadway. In this work, the Intelligent Driver Model (IDM) developed by M. Treiber and others (Treiber et al (2000a), Treiber et al (2000b)) is used as the microsimulation model. The IDM has a limited number of parameters and an intuitive algorithm. These authors have calibrated the IDM against data obtained for three German highways (Treiber et al 2000b). The IDM parameters used in this study are similar to his values, but are taken to be stochastic variables with small variation. Two relevant parameters are given the values:

- Desired velocity: taken as normally distributed; *N*(110 km/h, 7.0 km/h) for cars and *N*(90 km/h, 3.6 km/h) for trucks;
- Safe time headway: taken as normally distributed; *N*(1.2 s, 0.05 s) for cars and *N*(1.5 s, 0.05 s) for trucks;

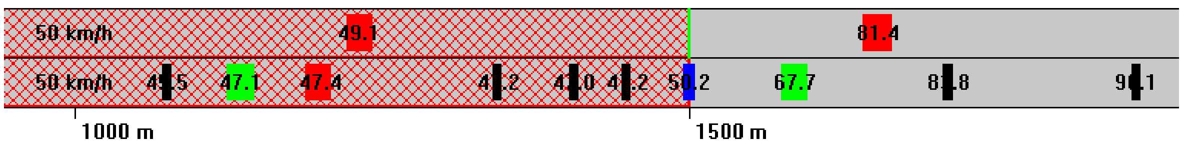

Figure 1 – Microsimulation modelling in progress.

As shown in Figure 1, the vehicles were 'driven' on a 2 km road section using the IDM. A speed limit of 50 km/h was defined from 500 m to 1500 m. Vehicles' arrival times at a virtual loop detector (located at the start of the speed limit region) were output. These arrival times constitute the microsimulation headway between successive vehicles. This road layout was used for microsimulation processing of both the standard free-flow and congestion models.

4. Simulation Results

In this study, 50 days of traffic is generated for the free-flowing models whilst 240 hours of continuous traffic is generated for the congested models. The days of free-flowing traffic represents 10 weeks of data of 5 working days per week. It is taken in this study that there are a total of 4 hours of congestion per working day and so the 240 hours of congested traffic represents 60 working days or 12 weeks of data. For each of the main models traffic compositions of 0%, 50% and 90% cars are considered.

Three load effects are considered for two-lane bi-directional bridges:

- Bending moment at the centre of a simply supported span;
- Bending moment over the central support of a two-span bridge;
- Left hand shear force of a simply support span.

Each of these load effects are considered for bridges of 20, 30, 40, 50 and 60 m lengths. This arrangement of load effect and bridge length is considered to represent a wide range of influence line shapes and the majority of highway bridge stock.

4.1 Calibration Results

To assess the impact of the stochastic nature of the MS-IDM upon resultant load effects, a traffic file was generated using the SCM. This traffic file was then processed using the MS-IDM 5 times. It was found that a higher percentage of cars results in more variability of the resulting lifetime load effect. Noting that in both cases the volume of trucks is constant, the increased variability must be due to the wider range of traffic scenarios caused by an increased number of vehicle-to-vehicle interactions.

Five sets of traffic data were generated to the SCM with nominal gaps of 5, 10 and 15 m. No cars were included in the files. These runs were then processed using the MS-IDM. Before and after the application of microsimulation, the mean resulting load effect was calculated. It was found that the microsimulation mean result is least onerous, whilst the SCM with 5 m nominal gap can have load effects over 50% greater for a bridge length of 60 m. This difference reduces with span. Of note, the microsimulation results are similar to results obtained for the SCM with 15 m nominal gap. This may prove useful in future studies.

To assess the impact of differing car percentages, whilst maintaining constant truck volume, 5 samples of each of the following were calculated:

- The SCM using a 5 m nominal gap;
- The MS-IDM, based upon the SCM with 5 m nominal gap;
- The SFFM, based upon the measured Auxerre traffic;
- The MS-IDM based on the SFFM traffic.

In each case the average lifetime load effect for the five runs is calculated. Using this value of load effect for the 0% Cars simulation as a basis, the average difference of load effect for each bridge length and traffic scenario is found, as shown in Figure 2.

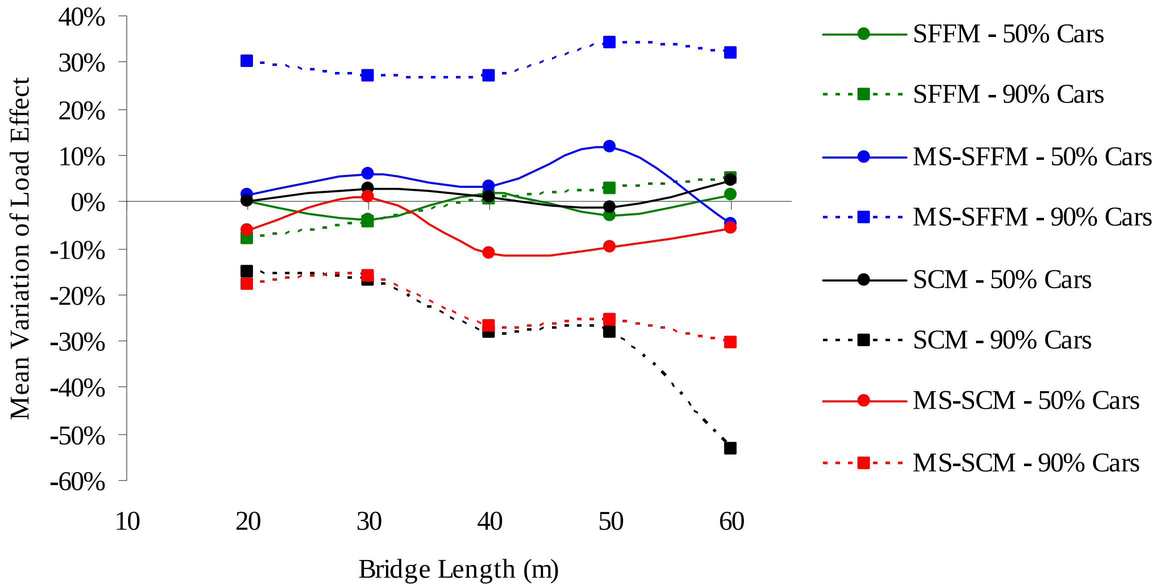

Figure 2 – Variation in average load effect values due to traffic model and percentage cars.

Figure 2 shows that the standard free-flow model (SFFM) results are not affected by the introduction of cars. This is reasonable since trucks headways are independent of cars in any case. Interestingly, using microsimulation on the same traffic files causes an increase in load effect; significantly so for 90% Cars. Examination of the flow-density graphs produced during the microsimulation reveals that with 90% cars the capacity of the road is reached and congestion results and this is not the case for 0% and 50% Cars. Further, it can be seen for both the SCM and microsimulation processed SCM traffic (MS-SCM), that load effect reduces with the increased percentage of cars as may be expected. This is as a result of the spacing out of trucks, reducing the overall intensity of load on the bridge surface.

4.2 Effect of Traffic Microsimulation

All 5 sets of generated traffic files from both the congestion model (SCM) and free-flow model (SFFM) were processed using the traffic microsimulation model (MS-IDM) to produce new traffic scenarios for the cases of 0%, 50% and 90% cars. Load effects for all bridge lengths were calculated both before and after the application of the traffic microsimulation model. Whilst differences exist between load effects, the differences are more pronounced between the percentages of cars, and so the mean difference of the load effects was taken.

Figure 3 shows the mean change in load effect that occurs by the application of traffic microsimulation. Immediately apparent is that load effect increases significantly when microsimulation is applied to the free-flow model when the traffic is comprised of 90% cars. This phenomenon is explained by the large number of vehicles which result in congestion on the microsimulation road, even though the arrival times to the start of the road were generated according to a free-flow model. The final values of load effect are close to those caused by congested models, as would be expected. The other aspect of the results that is obvious is the general trend for load effects to reduce for all other traffic models and composition. In fact applying microsimulation to the congestion model reduces load effect significantly. This was identified previously in Figure 3, where it was observed that microsimulation effectively spaces out congested traffic so that a 15 m nominal gap gives similar results. Besides the increase in load effect for 90% cars, the application of microsimulation to free-flow model-generated traffic results in smaller reduction in load effect. This is as may be expected since a free-flow model should more closely resemble driving traffic than a congested model.

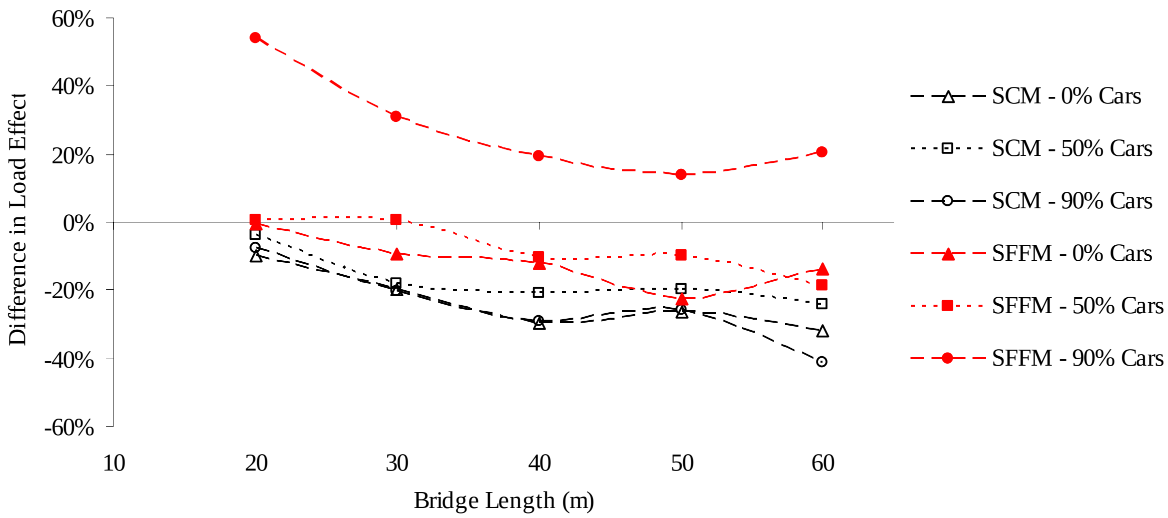

Figure 3 – Impact of traffic microsimulation on load effect.

4.3 Governing Form of Traffic

Recent research (Caprani (2005)) suggests that DAFs at the lifetime level may not be nearly as high as previously thought. It is useful to consider a critical value of DAF which is required in order for free-flowing traffic regimes to govern. Thus, as knowledge about lifetime DAF values becomes more available, it is easier to assess the governing form of traffic. As a simplification, we take the average load effect predictions from the three traffic compositions considered. Dividing the congested model results by the free-flow model results gives us this 'Required DAF'. Figure 4 shows the values of Required DAF for each load effect, alongside the Eurocode values of DAF for comparison. In this figure, once the required DAF is larger than the design DAF, congested traffic governs. Thus congested traffic governs above lengths of about 52 m, 33 m and 45 m, for Load Effects 1, 2 and 3 respectively.

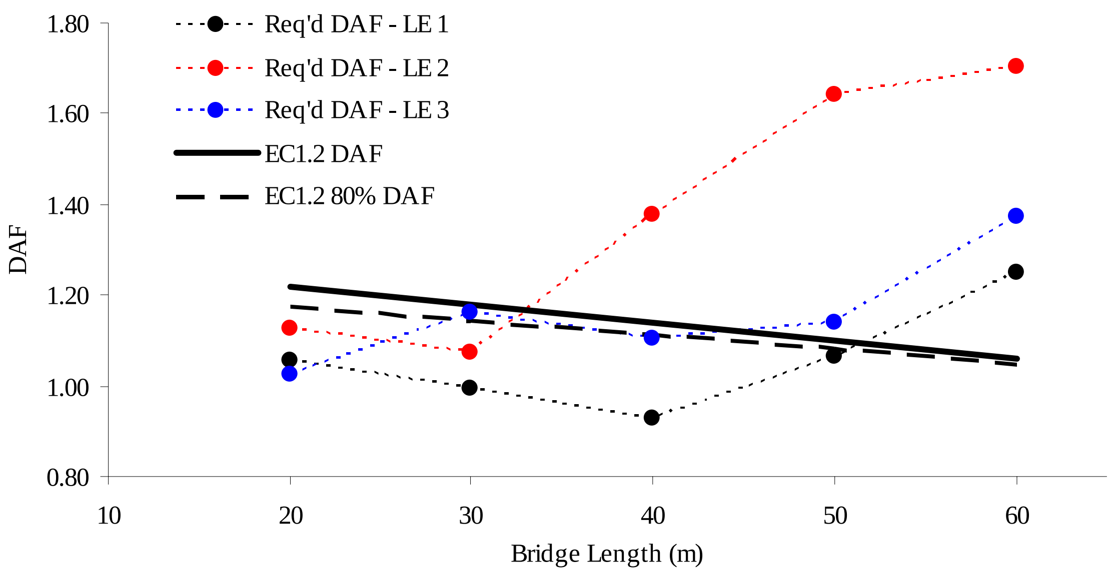

Figure 4 – Identification of governing traffic state through required DAF.

From Figure 4, it is also possible to assess the impact of a postulated reduction in the dynamic increment of 20%. For example, the DAF of 1.20 has an increment of 20% which, when reduced by 20% results in a DAF of 1.16 – called EC1.2 80% DAF in the figure. Due to the slopes of the various lines, this change may have small or significant impact. Such a reduction in DAF means that congestion would now govern for lengths of about 50 m, 32 m and 38 m, for Load Effects 1, 2 and 3 respectively. Evidently, the small change in DAF has resulted in a large change in the bridge length above which congested traffic governs for Load Effect 2.

5. Conclusions

The results of this work show that the variability of load effect through the application of a stochastic microsimulation model is not insignificant and so repeated generations of traffic scenarios are important to ascertain sensitivity. The microsimulation model results suggests that standard congestion models are very conservative – a nominal gap of 15 m may be more appropriate than a nominal gap of 5 m. Further, the introduction of cars into the models can both reduce load effects (in the case of congested models) and increase load effects (in the case of free-flow models with a high percentage of cars), once the microsimulation model is applied. For car percentages of 0% and 50% the change in load effect was not large. For a car percentage of 90% load effects changed significantly. This suggests that lifetime load effect is very sensitive to high percentages of cars. We also showed that the application of traffic microsimulation tends to reduce overall lifetime load effect values, in comparison to the standard free-flow and congestion models. Lastly, it was found that the governing form of traffic is sensitive to the values of DAF applied to free-flowing traffic. Indeed, even given current DAF values, the governing form of traffic can be less than expected for some load effects (in particular, Load Effect 2). Until further research is carried out into lifetime values of DAF, it will be difficult to adequately state governing forms of traffic for different bridge lengths. In addition, since the governing form of traffic is shown to depend on the load effect considered, it seems prudent to consider both traffic states in any bridge assessment. This being the case, traffic microsimulation is shown to be an ideal tool for this purpose.

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