Using Microsimulation to Estimate Highway Bridge Traffic Load

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ABSTRACT: In bridge traffic loading there is an often-made assumption that free-flowing traffic incorporating dynamic effects governs for spans up to about 40 m and that thereafter congested traffic governs. This study uses traffic microsimulation as a basis for the comparison of regularly-used free and congested traffic flow models. Traffic microsimulation offers a comprehensive approach to the modelling of traffic as it models individual vehicle and driver behaviour giving a more realistic picture of traffic states and their consequent load effects on bridges. For a range of bridge lengths and load effects, and for each traffic model, a dynamic ratio that would be required for free-flowing traffic to govern is determined. It is shown that this required dynamic ratio is higher than that expected for a range of spans and load effects. This work concludes that, for a range of spans, the governing form of traffic may be congested traffic, contrary to the common assumption made in bridge traffic load estimation.

1 INTRODUCTION

1.1 *General*

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 gives confidence in the lifetime load effect estimation.

In the process of calculating load effect just outlined, 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.

1.2 *Traffic Models*

Free-flow traffic models have been used for many years to model highway bridge loading (Caprani (2005)). Regularly, measured parameters such as speed and hourly flow rates are 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, as is further explained.

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.

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. One particularly appropriate such model is the Intelligent Driver Model (IDM) developed by M. Treiber and others (Treiber et al (2000a), Treiber et al (2000b)). 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).

2 BRIDGE & TRAFFIC MODELING

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 it is acknowledged that this results in conservative loading for a 2-lane bi-direction 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. Truck traffic characteristics, such as weight and dimensional data, were collected for the trucks.

2.2 *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).

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*

Extreme value statistical theory is used in this work to analyze 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:

$$G_i(s) = \exp\left\{-\left[1-\xi_i\left(\frac{s-\mu_i}{\sigma_i}\right)\right]_+^{1/\xi_i}\right\} \qquad (3)$$

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:

$$G_C(s) = \prod_{i=1}^{N} G_i(s) \tag{2}$$

In which N is the number of event types, $G_j(\cdot)$ is the GEV distribution of the j-truck loading event. We consider there to be 250 working days per year, and extrapolate load effects to determine the return level for a return period of 1000 years, as specified by the Eurocode (EC1.2 2003). We stress that this is not the design life of the structure, which may be taken as 50 or 100 years. In such cases the probability load effect exceeding the return level is approximately 5% and 10% respectively.

2.5 *Bridge and Road Configuration*

Bridges with two opposing lanes of lengths in the range 20 to 60 m are considered. The load effects examined are:

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

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.

For the simulations involving microsimulation, the vehicles were ‘driven’ on a 2 km road section. 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. These are also considered as the arrival times at the left hand end of the bridge, thus locating the bridge relative to the road layout.

3 TRAFFIC MODELS

3.1 *General*

The traffic models used in this study are next described. Traffic models describing free-flowing and congested traffic are explained: we have termed these the standard free-flow model (SFM) and the standard congested-flow model (SCM) since they are taken to represent the state-of-the-art in traffic models for highway bridge loading. Secondly, the microsimulation model and algorithm is explained.

3.2 *Standard Free-Flow Model (SFM)*

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.

For headways of less than 1.5 seconds a distribution of headway that is independent of flow is used. This approach is supported by the theory that, for small headways, driver perception of safe distance rather than traffic flow determines the headways (Koppa, 1992; Lieberman and Rathi, 1992). Two quadratic curves are used to describe the headway cumulative distribution function (CDF) in this region, as shown in Figure 1.

For headways between 1.5 and 4 seconds, there is a correlation between headway and flow. The available data was categorised by hourly flow in intervals of 10 trucks per hour resulting cumulative distribution functions for headway given in Figure 2.

For headways above 4 s, the normalized negative exponential distribution of Crespo-Minguillón and Casas (1997) is used, described by:

$$F(t) = \frac{Q}{3600}\left[1 - e^{-\lambda t}\right] \tag{2}$$

where λ is the mean normalised headway and Q is the flow (trucks/hour).

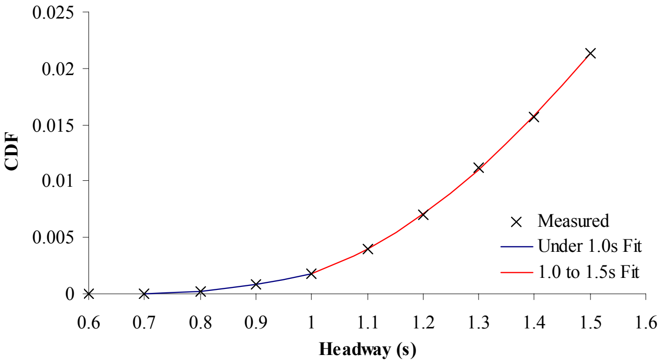


Figure 1. CDF of SFM headways of under 1.5 s.

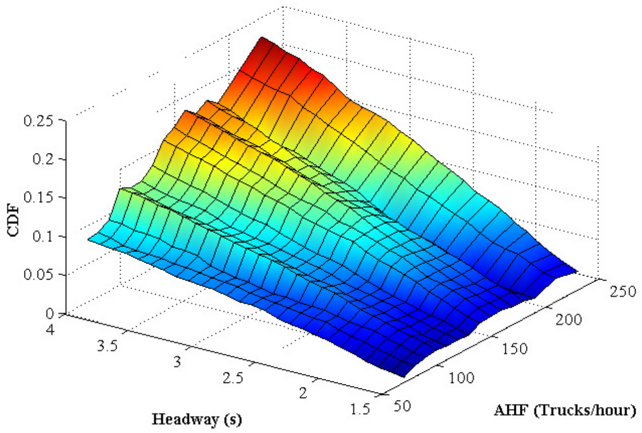


Figure 2. CDFs of headways between 1.5 s and 4 s by average hourly flow (AHF).

3.3 *Standard Congested-Flow Model (SCM)*

For congested flows, the literature has adopted constant spacings between trucks which vary from about 4.5 to 10 m. 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. This model is illustrated in Figure 3.

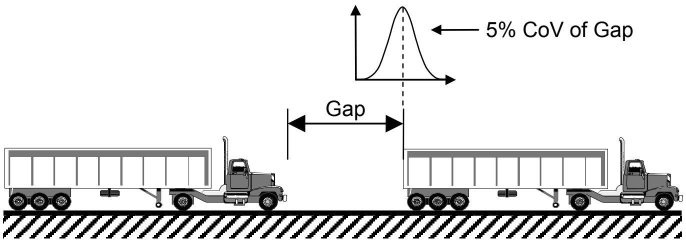


Figure 3. Illustration of the Standard Congestion Model (SCM) for this study.

3.4 *Traffic Microsimulation Model (IDM)*

The Intelligent Driver Model (IDM), developed mainly by Treiber (Treiber et al (2000a), Treiber et al (2000b)) is a microscopic driving model. Its equations describe the motion of an individual vehicle in response to its surroundings, given some mechanical and driver performance parameters. In particular the IDM is based on the idea that a driver tries to minimize braking decelerations. The acceleration a vehicle undergoes is defined by:

$$\dot{v} = a\left[1-\left(\frac{v}{v_0}\right)^{\delta}-\left(\frac{s^*}{s}\right)^2\right]. \tag{3}$$

This expression combines the vehicle's acceleration towards the desired velocity, v_0, where a is the maximum acceleration and δ is the velocity exponent (taken as 4), with the vehicle's decelerations due to interaction with the vehicle in front, based upon the ratio of the current gap, s, to the desired minimum gap, $s*$, described by:

$$s^* = s_0 + s_1\sqrt{\frac{v}{v_0}} + vT + \frac{v(\Delta v)}{2\sqrt{ab}}. \tag{4}$$

in which s_0 and s_1 are the minimum and elastic jam distances respectively, T is the desired time headway, Δv is the approach velocity to the leading vehicle, and b is the comfortable deceleration.

The IDM parameters used in this study are taken as per Treiber (2000a), 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.

4 SIMULATIONS AND RESULTS

4.1 *Description of Study*

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. In all studies, 5 sets of data were generated and processed to ascertain repeatability.

All 5 sets of generated traffic files from both the congestion model (SCM) and free-flow model (SFM) were processed using the traffic microsimulation model (MS) 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. In this way the impact of traffic microsimulation can be examined with reference to traditional traffic models, whilst keep the same underlying traffic constant.

4.2 *Initial Results*

To assess the impact of the stochastic nature of microsimulation upon resultant load effects, a traffic file was generated using the SCM. This traffic file was then run 5 times along the road. 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 5 m nominal gap (SCM – 5 m). No cars were included in the files. These runs were then processed using microsimulation model; their mean resulting load effect provides a benchmark to assess other nominal gaps of the SCM. Single traffic files were generated using the SCM for nominal gaps of 5, 10 and 15 m. These traffic sets were then used to calculate their lifetime load effects. A sample result is shown in Figure 4. Similar results were obtained for the remaining load effects. It can be seen that the microsimulation mean result is least onerous, whilst the SCM – 5 m is most onerous. Further, and of interest for further studies, the microsimulation results are similar to the results obtained for SCM – 15 m. This gives an indication of the conservatism built into the 5 m gap assumption of past studies.

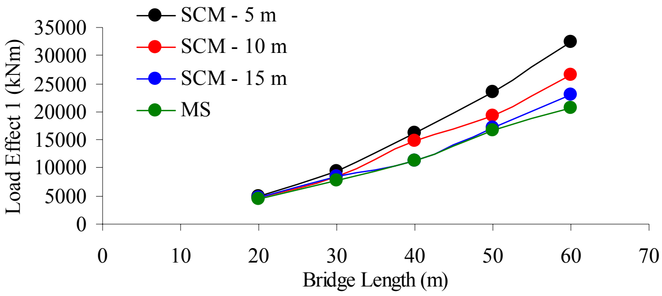


Figure 4. Variation of Load Effect 1 with congested traffic model. The MS data are the microsimulation results.

4.3 *Sample Results Considering Load Effect 1*

For Load Effect 1, the comparisons between the microsimulation and standard model results for congested traffic are shown in Figure 5. It is clear to see that the SCM results (the more traditional approach) gives significantly higher values of load effect than the microsimulation results for a very wide range of traffic composition (0 to 90% cars). Further, since the micro-simulated 90% cars is approximately typical motorway traffic composition and behaviour ("MS - Cars 90%" line), and since code calibration study neglect cars and adopt a standard model (the "SCM - Cars 0%" line), the conservatism of the code calibration studies can be clearly seen.

Also for Load Effect 1, the comparison between the standard and microsimulation results for free-flowing traffic is shown in Figure 6, from which there are some interesting observations to be made. Firstly, the standard free-flow model (SFM) results are remarkably similar, regardless of the percentage of cars. However, this is to be expected since the SFM accounts for the cars in the truck to truck headway model. Secondly, the microsimulation model load effects are generally less than those of the SFM, with the exception of the 90% cars scenario. Thirdly, it is clear that the 90% cars scenario does not follow the trends of other car percentages in the associated microsimulation load effects are greater than those of the standard approach. This phenomenon is caused by the fact that since truck volumes are kept constant, a 90% cars scenario requires a large volume of traffic overall. This large volume of traffic, when processed using microsimulation, results in congested traffic crossing the bridge as shown by the flow-density relationship in Figure 7 obtained from the virtual loop detector data in the road. This congested traffic state has consequent higher load effects, yielding the observed phenomenon of Figure 6. In fact this illustrates a drawback of the standard approach: it is possible to generate traffic from a free-flowing model that is, in fact, not free-flowing.

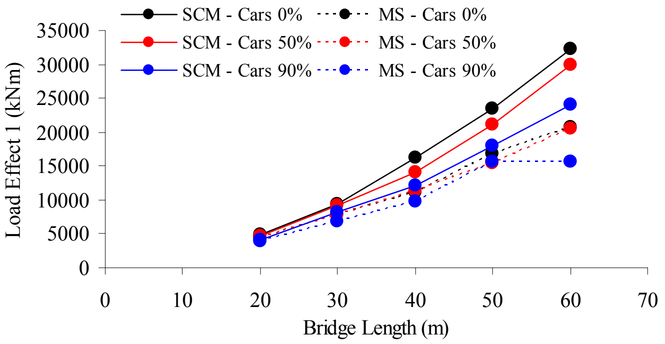


Figure 5. Variation of Load Effect 1 by congested traffic model and percentage of cars.

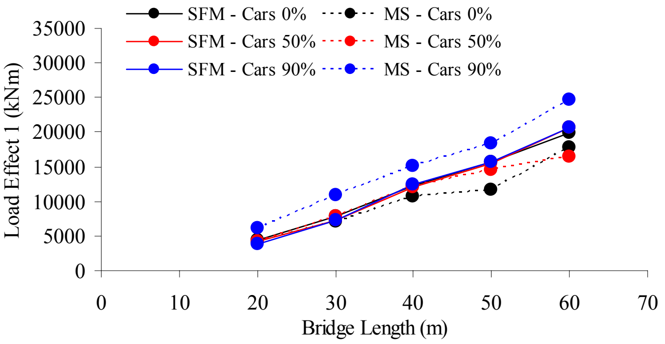


Figure 6. Variation of Load Effect 1 by free-flow traffic model and percentage of cars.

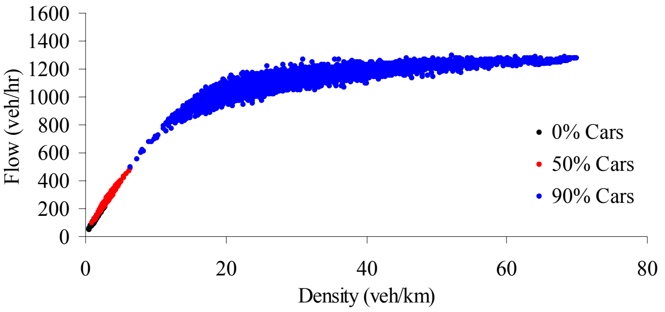


Figure 7. Flow-density plot for free-flow traffic scenarios from microsimulation model.

4.4 *Comparison of Microsimulation and Standard Traffic Model Results*

The analyses outlined for Load Effect 1 were repeated for the other two load effects. Considering the microsimulation results as the base, the variation of the resulting load effects are given in Figure 8.

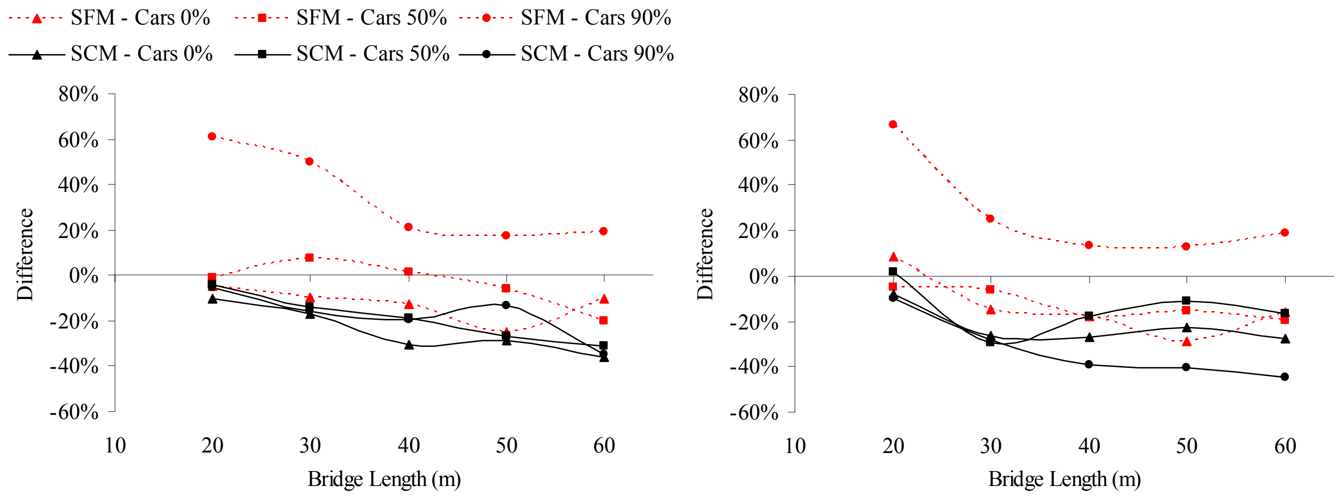
Immediately apparent for all three load effects is that load effect increases significantly when microsimulation is applied to the 90% cars free-flow model. This phenomenon is explained previously for Load Effect 1. In this scenario, the final values of load effect are actually close to those caused 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 4, 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 (Figure 8(d)). This is as may be expected since a free-flow model should more closely resemble driving traffic than a congested model.

4.5 *Implications of Results on The Governing Form of Traffic*

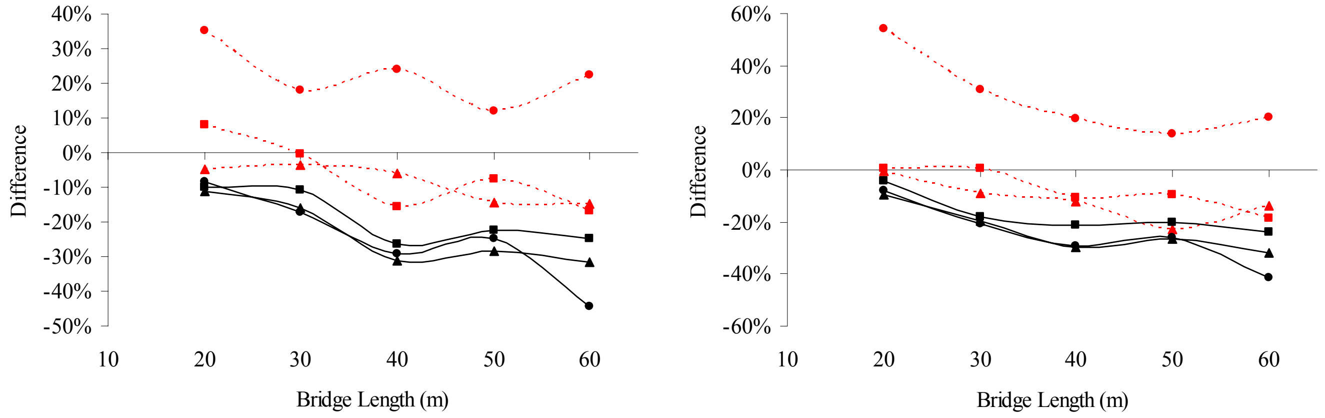
Recent research (Caprani (2005)) suggests that DAFs at the lifetime level may not be nearly as high as previously thought. It is useful to consider a critical value of DAF which is required in order for free-flowing traffic regimes to govern. Thus, as knowledge about lifetime DAF values becomes more 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’ (the DAF required for free-flowing traffic to govern).

Figure 9 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.



(a) Load Effect 1;

(b) Load Effect 2;



(c) Load Effect 3;

(d) Average of all three load effects;

Figure 8. Variation of free-flow and congested flow results from microsimulation results by load effect and car percentage.

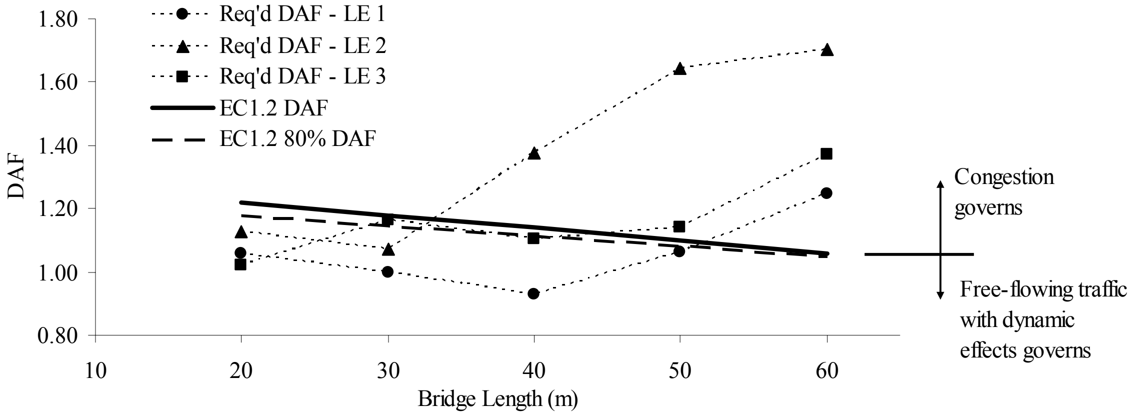


Figure 9. Indentifying the governing traffic state through dynamic amplification measures.

From Figure 9, 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 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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