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A NEW CONGESTED TRAFFIC LOAD MODEL FOR HIGHWAY BRIDGES

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Abstract
Long span highway bridges are critical components of any nation's infrastructure. Therefore accurate assessment of highway bridge loading is essential, and it is well known that congested traffic governs load effect for such bridges. Current congestion models use conservative assumptions about traffic and inter-vehicle gaps. This research investigates congested traffic flow through the use of traffic microsimulation which has the ability to reproduce complex traffic phenomena based on driver interactions. A time series model has been developed to produce a speed time-series similar to the results of the microsimulation. The speed time-series from the new model, combined with the established speed-gap relationship from the microsimulation, form the basis of a more computationally efficient congested traffic model. It is shown that the new model replicates aspects of microsimulation traffic well. However, the resulting load effects do not match as well as expected, and so further development of the model is required.

Keywords: Bridge; Congestion; Gap; Loading; Microsimulation; Speed; Traffic.

1. Introduction

Long span bridges usually form a critical part of a country's highway infrastructure. Since they are difficult and expensive to construct in the first place, they therefore only exist where there are clear economic imperatives. To remove such a structure from service, even if only temporarily, would therefore cause large-scale disruption. The economic costs associated with this are usually several orders of magnitude greater than any rehabilitation costs. Thus the prime motivation is to minimize disruption through accurate assessment of the structure's rehabilitation needs.

In any highway bridge structure assessment, live loading is one of the most variable parameters and so its accurate assessment can have significant impact on the rehabilitation needs of the structure. For long-span bridges, congested traffic is known to be the critical live loading scenario. Therefore its accurate modelling is essential for minimizing rehabilitation and its associated costs.

The modelling of congested traffic that has been described in the literature has been based on some simplifying and conservative assumptions. For example, Nowak and Hong (1991) modelled 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. And 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.

This work examines congested traffic flow through the use of traffic microsimulation, which has the ability to reproduce complex traffic phenomena based on driver interactions. Congested traffic can be induced in microsimulation through artificial speed limits. A speed-gap relationship for different traffic densities can be determined. The traffic microsimulation model is computationally expensive and so only limited amounts of data can be obtained whereas long run simulations are required for bridge loading assessment. This work develops a computationally efficient congested traffic model based on the speed-gap relationships.

2. Traffic Modelling

2.1 Site and Vehicle Characteristics

This work uses weigh-in-motion (WIM) data obtained from the A4 (E40) at Wroclaw, Poland. In total over 17 weeks of traffic was recorded, including cars, from 1 January 2008 to 5 June, 2008. Both lanes of traffic in one direction were measured.

In this work, the arrival of each successive vehicle in a lane is considered to be a Markov process. The transitional probability matrices for each lane are calculated from the measured WIM data. These matrices are then used to generate the each successive vehicle arrival.

The properties of each vehicle are modelled as described by Enright (2010). For example, a bivariate distribution is used to model gross-vehicle-weight (GVW) and the number of axles of the vehicle; axle spacing distributions (such as tri-modal normal) are defined for each vehicle type; and axle weights are defined using bi-modal normal distributions representing the percentage GVW carried.

2.2 Vehicle Overhang Database

The bridge loading caused by a stream of congested traffic is static in nature, due to the low speeds involved. For a given set of vehicles, larger load effects will result from more closely spaced vehicles. In particular, higher load effects will result from closer front and rear axles of successive vehicles. The parameters influencing the gap between adjacent front and rear axles are not only those of driving characteristics, but include the vehicle front and rear overhangs (i.e. distance from the front and rear of the vehicle to the front and rear axles respectively).

Vehicle overhangs are difficult to obtain from site measurements. Therefore, for this research, a database of vehicle information was compiled from information supplied by European vehicle manufacturers. Over 1000 vehicles are included in this database. These vehicle dimensions, along with other published data (Page and Ricketts 1997), were used to categorize vehicles by axle configuration.

3. Congested Traffic Model Development

3.1 Microsimulation Analysis

In order to account for the influence of driving behaviour on the gaps between vehicles in congested traffic, traffic microsimulation has been used. The Intelligent Driver Model (IDM) developed by Treiber and others (Treiber et al., 2000a, Treiber et al., 2000b) is used for this purpose. The program, *EvolveTraffic* (Caprani and OBrien 2008, Caprani 2010), implements the IDM and is used for this study.

The WIM data are processed using *EvolveTraffic*. Congested traffic is induced, similar to Treiber (2000b), using artificial speed limits (10, 15, 20 and 25 km/h).

These induce varying densities of 74 to 102 vehicles/km/lane. As the density increases over about 74 vehicles/km/lane congestion results. Kerner et al. (2004) state that when the average traffic speed is less than 24 km/h it can be considered as congested.

The 'virtual' road used in this study is 3 km long, with two lanes in the same direction. At 2800 m a speed limit, 200 m in length, is imposed to induce congestion. The data outputted from the microsimulation includes traffic speeds at 10 s intervals. Also, individual vehicle data, including the vehicle time-stamp and the vehicles length, including overhangs are output, which allow inter-vehicle, bumper to bumper gaps to be calculated. By averaging the inter-vehicle gaps over 10 second intervals, a speed-gap time-series is found (Figure 1).

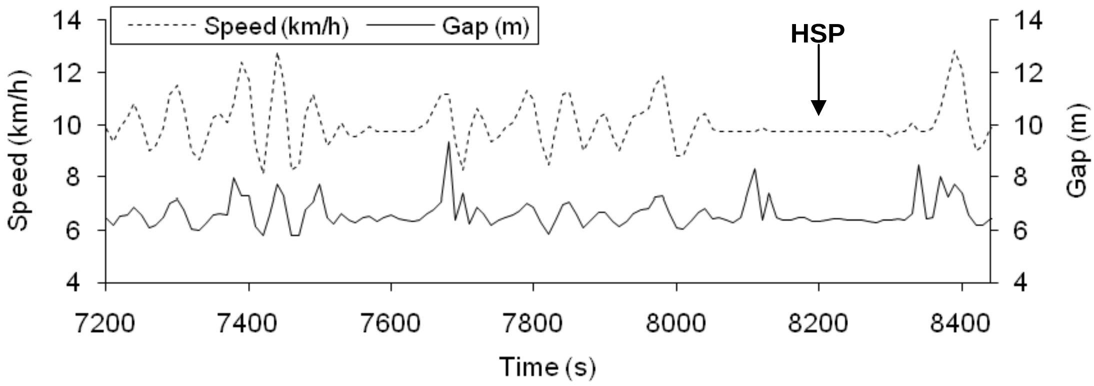

Figure 1 – Typical observed speed and gap time-series (see Section 3.3 for HSP).

3.2 Congested Traffic Speed-Gap Relationship

Traffic theory suggests that the speed-gap relationship is not monotonic: different gaps are found for similar speeds; depending on the phase (acceleration or deceleration) the traffic is experiencing (Kerner et al 2004). However in the congested traffic flow produced by the microsimulation, no hysteresis in the speed-gap relationship was observed (Figure 2), as the acceleration and deceleration phases are of low amplitude (below 0.2 m/s^2).

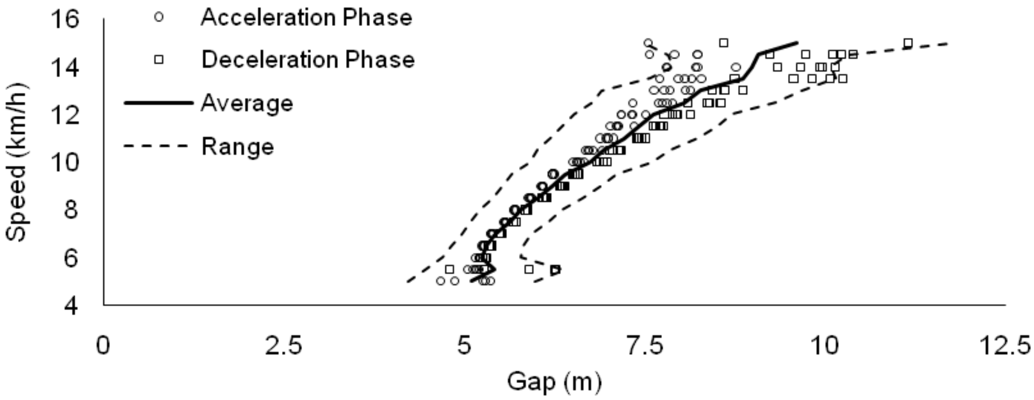

Figure 2 – Observed speed-gap relationship for density range 80-86 veh/km/lane.

3.3. Congested Traffic Speed Model

In the microsimulation modelling, periods for which traffic travels at a constant speed, labelled here as homogeneous speed phases (HSP), were observed (see Figure 1 for an example). Due to the non-stationary caused by the presence of HSPs, an autoregressive time-series model, such as ARIMA (Boxx et al. 2008) is not an appropriate model. Therefore, to model speed, the change of speed is calculated at each time-step and plotted against the current speed of each vehicle (Figure 3). This bivariate distribution is discretized for the speed ranges shown. Thus, given a particular speed, and whether the traffic is accelerating or decelerating, the change in speed can be estimated probabilistically. The phase the vehicle is experiencing is modelled using a Markov transition matrix for each speed range (Table 1).

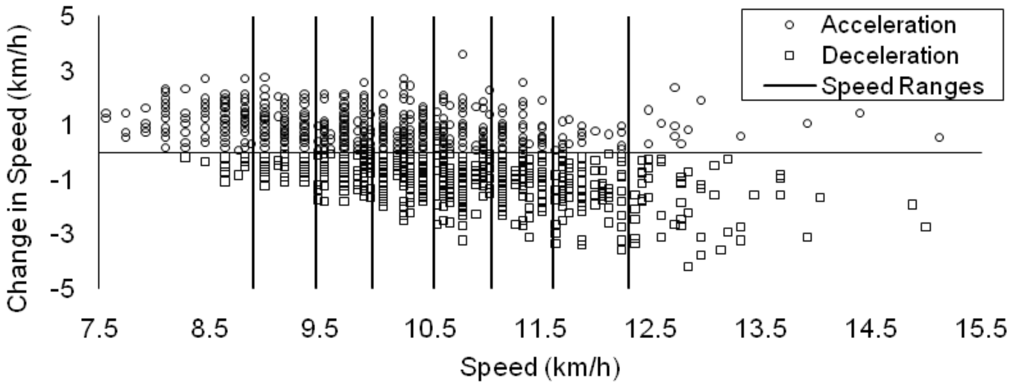

Figure 3 – Speed and phase identification (density range 74-79 veh/km/lane).

Table 1 – Traffic phase transition matrix for a density of 74-79 veh/km/lane.

Phase Transition*	**Speed Range (km/h)**						
	0-8.9	**8.9-9.5**	**9.5-9.8**	**9.8-10.5**	**10.5-11.1**	**11.1-12.0**	**12.0+**
A - A	1.00	1.00	0.98	0.69	0.53	0.34	0.26
A - D	0.00	0.00	0.02	0.31	0.47	0.66	0.74
D - D	0.08	0.34	0.53	0.85	0.96	0.98	1.00
D - A	0.92	0.66	0.47	0.15	0.04	0.02	0.00

* A – Acceleration; D - Deceleration

For a given traffic density there are specific speeds at which HSPs occur. The speed time series were analysed to identify the HSPs and determine the distribution of their duration. Further, the speed time series were analysed for the probability of an HSP occurring, for each particular speed.

3.3 Congested Traffic Model

The complete congested traffic load model proposed is determined from the congested traffic speed model and the established speed-gap relationship, with some variation applied (Figure 2). The following steps implement the model:

1. Randomly select a speed, based on the overall distribution of speeds;
2. Check if the speed is in a HSP, and if so the HSP duration;
3. From the bivariate relationship of Figure 3, determine the change in speed to find the speed in 10 s time;
4. Determine the particular phase (acceleration/deceleration) for the next speed, from the transition matrix (Table 1) given the current phase.

4. Application of Proposed Congested Traffic Model

4.1 Comparison with Microsimulation

To determine the accuracy of the proposed congested traffic model, relevant macro-statistics are compared to those from the full microsimulation in Figure 5 and Table 2. A typical speed time series obtained from the proposed model is shown in Figure 4, alongside a sample from full microsimulation.

The occurrence of different vehicle types in the proposed model is compared to those from the full microsimulation in Figure 6. The percentage differences in the occurrence of different vehicle types increases with the number of axles. This can be attributed to the relatively small number of such vehicles.

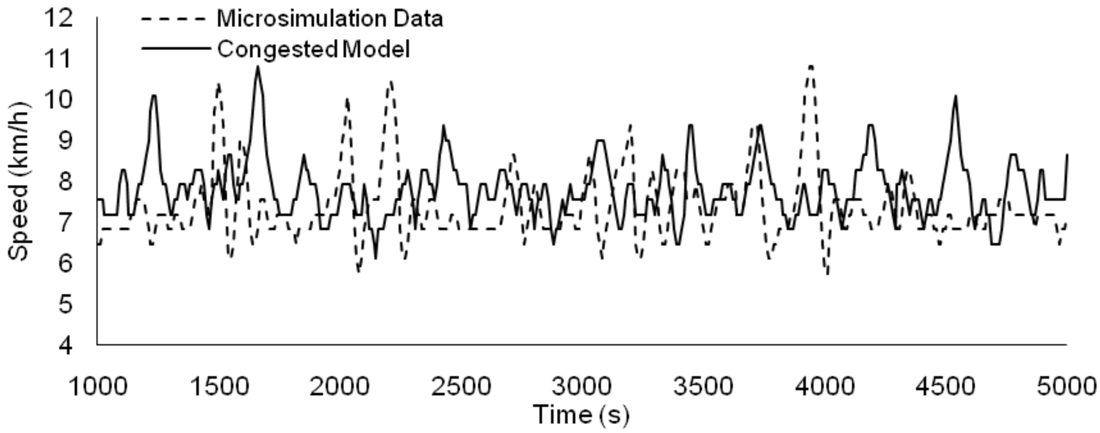

Figure 4 – Speed time-series from microsimulation and from congested model.

Table 2 – Proposed model and microsimulation statistics.

		Maximum	Minimum	Mean	Standard Deviation
Speed (km/h)	Microsim.	15.12	5.4	7.66	1.11
	Model	15.23	5.36	7.63	1.09
Gap (m)	Microsim.	12.64	1.54	5.67	0.74
	Model	12.88	1.71	5.71	0.77

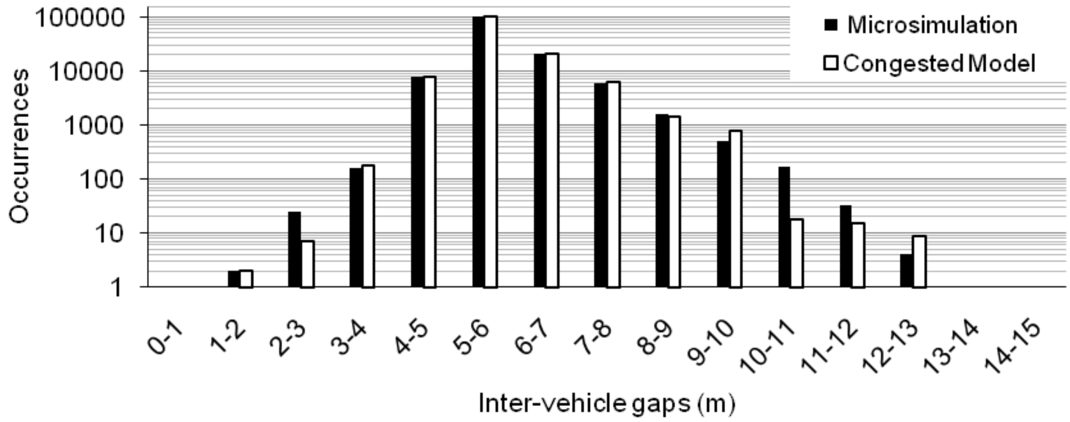

Figure 5 – Comparison of inter-vehicle gap distributions.

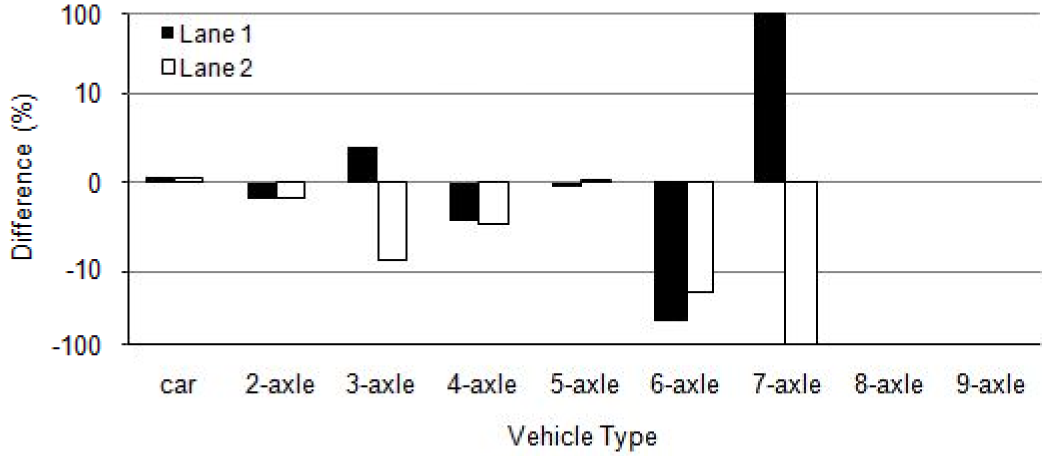

Figure 6 – Comparison of vehicle-type occurrence.

4.2 Comparison of Load Effects

The load effects resulting from the proposed congestion model are compared with those imparted by congested traffic from the microsimulation model, based on the WIM data. The bridge lengths and load effects considered are:

- Lengths: 40, 60, 80, 100 m;
- Load Effects:
    - LE1: Mid-span bending moment in a simply-supported beam;
    - LE2: Central support hogging moment in a two-span beam;
    - LE3: left hand shear in a simply-supported beam.

The simulations are 200 hours of congested flow, representing 100 days of traffic. Maximum-per-day load effects are fit with a Generalized Extreme Value distribution and the 1000-year return level of load effect estimated.

The return levels of load effect are calculated for the proposed model and from the full traffic microsimulation. The results are expressed as a ratio in Figure 7. This figure shows that load effects are consistently underestimated by the proposed model.

The GVW distributions used in both models are identical. Therefore, since LE3 gives a measure of the total load on the bridge, and since this is relatively uniform, it appears that an insufficient number of vehicles are present on the bridge. Thus it appears that the inter-vehicle gaps generated in the proposed model are not small enough for extreme loading scenarios.

The congested model underestimates load effects 1 and 2 also. Thus it appears that the generated gaps are not small enough at the critical influence line locations. However, given that the macro-statics of Table 2 show that the gap distributions are similar, it may be that the mode does not associate small gaps with heavy vehicles to the same extent that traffic microsimulation does. Perhaps, since heavier vehicles have less capacity to accelerate or decelerate, the gap distribution may be different for such vehicles than it is for light vehicles. Therefore the inter-vehicle gaps should be related to the vehicle GVW and are not just based solely on the vehicle speed.

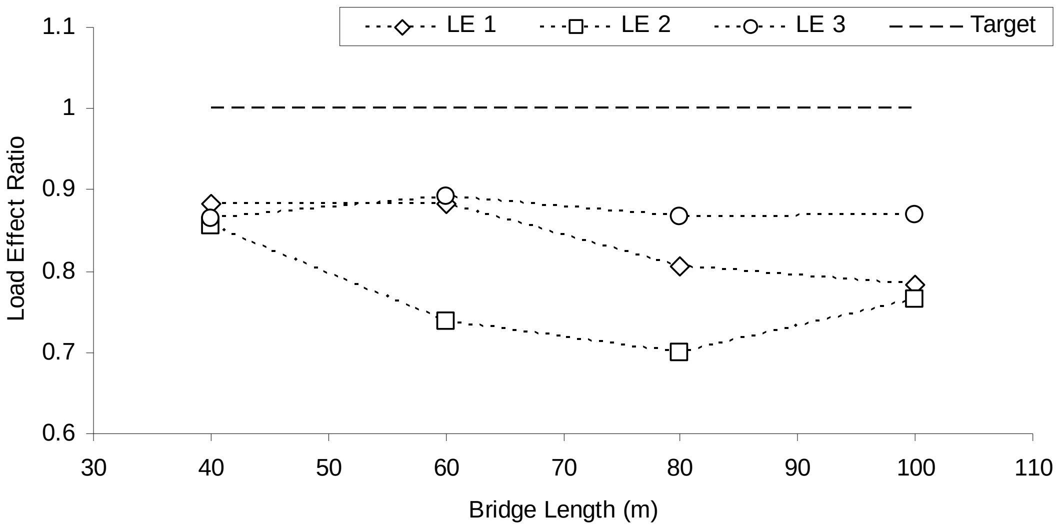

Figure 7 – Ratio of extreme load effect found from the congested model to that of the traffic microsimulation applied to the WIM data.

5. Summary

A new congested traffic model for long-span bridge loading is presented. This model is based on microsimulation of site-measured data, in order to create realistic congested traffic streams. This congested traffic was analysed and a speed time-series model and a speed-gap relationship for given traffic densities were defined. A Markov process is used to generate vehicles from the WIM data. The congested traffic model output is compared to that from microsimulation and is shown to compare well. Extreme load effects were determined for both models. It is found that the congested traffic model underestimates load effects. As a result, it is concluded from this work that a relationship between inter-vehicle gaps and load intensity may exist.

6. Acknowledgment

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