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Micro-simulation of single-lane traffic to identify critical loading conditions for long-span bridges

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ABSTRACT

The traffic loading of long-span bridges is governed by congestion. Real-world observations show that congestion can take several different forms. Nevertheless, most previous studies on bridge traffic loading consider only queues of vehicles at minimum bumper-to-bumper distances. In fact, such full-stop queues are rare events, while in most cases congestion waves propagate through the traffic stream, so that on a bridge there are periodically times of closely-spaced vehicle concentrations and times of flowing traffic, where vehicles are more distant. In this paper, an acknowledged traffic micro-simulation model is used for generating congested traffic on a single-lane roadway encompassing two bridges (200 and 1000 m long). Two truck percentages are considered (20% and 50%) and different congestion patterns are analysed in relation to their traffic features and effects on bridge loading. It is found that for the case of 200 m span and 20% trucks slow-moving traffic results in greater loading than full-stop conditions. Finally, the frequency of occurrence of different forms of congestion is taken into account based on recent available data, rather than being assumed as in most previous research. It is found that considering only the widely-used full-stop conditions leads to an over-estimation of the characteristic total load by about 10% for the cases of 200 m span with 50% trucks, and 1000 m with 20% trucks; for the case of 1000 m span with 50% trucks, the over-estimation drops to nearly 5%. However, for the case of 200 m span with 20% trucks, considering only the full-stop conditions leads to a slight under-estimation of the total load.

1. Introduction

It has been long acknowledged that long-span road bridges are governed by congested traffic rather than free-flowing conditions [1]. In free-flowing traffic, vehicles have large gaps between them, while congestion implies long queues of closely-spaced vehicles. In congested conditions, vehicle–bridge dynamic interaction is not significant, since critical events occur at slow speeds [2,3]. The bridge length threshold between the two cases depends on many factors but it typically lies between 30 and 50 m [4–6].

Traffic loading for long-span bridges is not taken into account in most codes of practice. The use of short-span bridge load models for the design of longer spans is rather conservative, as the average intensity of loading tends to reduce with increasing span [2,7,8]. Excessive conservatism for existing bridges is an even greater problem as it may lead to expensive and unnecessary interventions. In fact, small differences in the traffic loading requirements may imply significant differences in the maintenance operation costs [9].

Real-world observations show that congestion can take different forms, as detailed in Section 2.2. However, most previous studies on bridge traffic loading consider only queues of vehicles at minimum bumper-to-bumper distances [1,2,7,8,10–14]. Micro-simulation models the behaviour of individual vehicles and allows the generation of observed congestion patterns, thus providing a valuable tool to study the effects of different congestion patterns and traffic compositions on long-span bridge loading. Comprehensive traffic modelling allows a realistic simulation of the traffic scenarios expected to occur on the bridge, and therefore more accurate safety evaluation and more efficient maintenance planning.

1.1. Data collection

Traffic weight data is based on either truck surveys, or, more recently, *weigh-in-motion* (WIM) measurements. However, it must be noted that many WIM devices deployed on highways can accurately weigh vehicles only at higher speeds and do not work well or

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at all in stop-and-go traffic. Furthermore, traffic data (such as vehicle counts or speeds) is mostly collected by means of *induction loops* (sometimes combined with WIM devices), which may not be reliable at very low speeds [15]. As a consequence, data is largely collected during free-flowing traffic conditions, which also occur more frequently than congestion, whereas data about slow-moving – and therefore closely-spaced vehicles – is lacking.

Free-flowing traffic measurements are suitable for the analysis of traffic loading on short-span bridges, whose critical loading is made up of one or two big vehicles (see for instance Buckland et al. [2]). In such cases, the inter-vehicle gaps (or headways) can be taken directly from the WIM database, or from a calibrated headway model [16]. However, in long-span bridges, congestion governs and the gaps in such conditions are mostly unknown, due to the above-mentioned lack of data at low speeds.

Not only is data collection problematic during congestion, but also the analysis of traffic data can pose some issues [17,18]. As traffic data is generally collected only at point locations, vehicle positions can only be estimated from such point measurements, typically under an assumption of constant speed. However, during congestion, speeds may vary significantly. Therefore the estimation of the maximum number of vehicles present on a stretch of road from point measurements may result in a significant loss of accuracy [19], and bridge loading is obviously affected by the number of vehicles actually present on the bridge. On the other hand, the use of spatial detectors (such as cameras) over a stretch of road allows the collection of the vehicle positions during congestion, without resorting to estimation. Although cameras are the best solution from a theoretical point of view, they have not often been used for several practical reasons, such as sensitivity to illumination changes, communication requirements for transmitting the large amount of data collected, or computational demands of post-processing [15]. They have however been deployed for research purposes [20–24] and are becoming more popular.

In bridge loading studies, only Buckland et al. [2] and Nowak et al. [8] state that they have used video recordings. Ricketts and Page [3] use videos at various UK sites for manual vehicle classification during congestion. OBrien et al. [25] manually analyse videos for a micro-simulation model calibration. Zaurin and Catbas [26] propose a procedure for automatically tracking vehicles in the context of bridge health monitoring.

1.2. Codes of practice and previous research on long-span bridge traffic loading

Research on traffic loading for bridges is often related to studies for developing codes and standards. Existing load models for long-span bridges account for the variability of truck weights, but often assume a mix of cars and heavy vehicles at minimum bumper-to-bumper distances [1,2,7,8,10–14], which are typically assumed due to the lack of such data, as discussed in the previous section.

The "normal" load model in Eurocode 1 [27] is based on traffic data collected at Auxerre (France), considering 100% trucks in the slow lane for jam situations [28], and later confirmed with a more extensive database [29]. Its application is valid for the design of bridges up to 200 m. Other national codes, for example the former British and the Italian ones, suggest loading values for longer spans [30,31]. A recently-withdrawn standard by the Highways Agency [32] prescribed two levels of *assessment live loading* for spans longer than 50 m in the United Kingdom; however, current British standards limit the application of the assessment live loading to 50 m [33].

The current load model by the American Association of State Highway and Transportation Officials (AASHTO) [34] may be considered to apply to "ordinary bridges" with spans up to 152 m [35,36], although, in the calibration of its current traffic load model, the maximum span considered is 60 m [37]. The AASHTO load model is lighter than that prescribed in the Eurocode [8]. Lutomirska [38] concludes that the AASHTO load model can be extended to most spans up to 1500 m. Previously, the American Society of Civil Engineers (ASCE) [39] recommended a load model for the design of spans up to 1951 m, based on the work of Buckland et al. [2]. For assessment, AASHTO [40] prescribes a "legal" vehicle for the rating of existing bridges longer than 60 m.

Besides codes and standards, Ivy et al. [1] record 5629 heavy vehicles on a long-span bridge in San Francisco; the trucks were all placed at an average distance recorded in the field. Harman et al. [10] develop a procedure for predicting live-load effects using traffic surveys. The Flint and Neill Partnership [7] uses truck surveys and free flow data to build up queues of heavy vehicles and cars; the results are then extrapolated to find the design bridge loading. Vrouwenvelder and Waarts [11] develop a load model based on data from the Netherlands, differentiating between free, congested, and full-stop traffic. Ditlevsen and Madsen [12] develop a theoretical framework for building up queues based on a cell discretisation of the bridge. Bailey and Bez [13] develop a methodology to derive probability distributions of extreme traffic actions based on site-specific data; they differentiate between traffic conditions of free, congested, and at-rest, and assign a probability distribution to gaps. Nowak et al. [8] use WIM data and videos of congested traffic to develop a design load model made up of an average heavy-vehicle queue on the slow lane.

Table 1 lists the assumed congested inter-vehicle gaps in selected models, as well as their stated span length application. Note that, in spite of the fact that such gaps are deemed representative of traffic at a standstill, the vehicles are generally moved along the bridge: the first vehicle is removed, the queue is then moved forward, and a vehicle is added at the other end of the bridge. All of these methods exclude the observed variability of congested patterns, with the exception of Vrouwenvelder and Waarts [11] and Bailey and Bez [13]; however, the underlying traffic models were quite basic, with all the vehicles moved at the same constant speed. Furthermore, the frequencies of occurrence of congestion are assumed or based on little data, and are generally rather conservative.

Recently, traffic micro-simulation has been used to achieve a more accurate traffic modelling, with special regard to the variability of inter-vehicle gaps, with the notable advantage that the widely-available free-flowing traffic measurements can be used as initial conditions for simulating congested traffic scenarios. OBrien et al. [25] study a long-span bridge in the Netherlands and calibrate a commercial micro-simulation tool using WIM data, videos and strain gauge measurements. Chen and Wu [41] use the *cellular automaton* approach (initially proposed by Nagel and Schreckenberg [42]), in which the bridge is divided into 7.5 m cells. However, the cellular structure does not allow for the variability of vehicle lengths and gaps between vehicles, and this is quite important in bridge loading. Caprani [43] uses micro-simulation to calibrate a simple congested load model for short- to medium-length

Table 1
Congested gap and span length application for selected existing load models.

Model	Congested gap (m)	Span length application (m)
Ivy et al. [1]	2.4	>120
ASCE (Buckland et al. [2])	1.5	15–1951
Flint and Neill Partnership [7]	0.9–1.8	75–1600
Vrouwenvelder and Waarts [11]	1–10	2–200
Eurocode 1 (Prat [14])	5[a]	5–200
Nowak et al. [8]	4.5	180–1500

[a] Between subsequent axles.