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# Long-span bridge traffic loading based on multi-lane traffic micro-simulation

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ABSTRACT

Long-span bridge traffic loading is governed by congestion. Although congestion can take various forms, most previous studies consider only a queue of vehicles. In this paper, traffic micro-simulation is used to generate several congested traffic scenarios on a two-lane same-direction roadway passing over two long-span bridges. To this end, an acknowledged car-following model is coupled with a lane-changing model. Different traffic compositions and several congestion patterns are analysed in relation to their traffic features and influence on bridge loading. It is found that: (a) slow-moving traffic may be as critical as the full-stop condition, depending on the span length; (b) critical long in-lane truck platoons form mainly at moderate inflows, typically occurring outside of rush hours; (c) the truck distribution between lanes has a limited effect on the total loading; (d) the presence of cars has a strong indirect influence on loading through their interaction with trucks. The methodology and the findings have relevance for computing a more accurate traffic loading for long-span bridges.



## 1. Introduction

It is widely accepted that long-span road bridges are governed by congested traffic rather than free-flowing conditions which govern for shorter spans [1]. In free-flowing traffic gaps between vehicles are large, whereas congestion implies queues of closely-spaced vehicles. Vehicle-bridge dynamic interaction is not significant during congestion, since vehicles are travelling slowly. The bridge length threshold between the two cases typically lies between 30 and 50 m [2–4].

Long-span bridge traffic loading is not addressed in most codes of practice. Eurocode 1 [5] applies only for the design of bridges up to 200 m. In the United Kingdom, the Flint and Neill Partnership [6] developed a design code for spans up to 1600 m. A recently-withdrawn standard by The Highways Agency [7] prescribed a reduction factor of the design load model for the assessment of spans longer than 50 m, but now the choice of a load model has to be agreed with the Overseeing Organization [8].

The live load model by the American Association of State Highway and Transportation Officials (AASHTO) [9] may be considered to apply to "ordinary bridges" with spans up to 152 m [10,11], although in the calibration of its current traffic load model the maximum span considered is 60 m [12]. Previously, the American Society of Civil Engineers (ASCE) [13] recommended a load model for the design of spans up to 1951 m, based on the work of Buckland et al. [14]. For assessment, AASHTO [15] prescribes a "legal" vehicle for the rating of existing bridges longer than 60 m.

The use of the available short-span traffic load models for long spans is quite conservative, as loading tends to reduce with increasing span [6,14,16]. Over-conservatism is an even greater problem for existing bridges, for which a small increase in traffic loading requirements may lead to a significant increase in maintenance operation costs [17].

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 [1,6,14,16,18–22]. However, research and experience suggest that other types of congestion may occur (e.g. *stop-and-go waves*).

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In recent years, micro-simulation has been used to achieve a more accurate traffic modelling for long-span bridges. Chen and Wu [23] use the *cellular automaton* approach [24], in which the bridge is divided into 7.5 m long cells, and consider lane-changing. However, such a cellular structure does not allow for the variability of vehicle lengths and gaps, which is quite important in bridge loading. OBrien et al. [25] study a long-span bridge in the Netherlands and calibrate a commercial multi-lane micro-simulation program. Their calibration is based on vehicle counts and strain gauge measurements, but the study lacks generality as conceived for a specific bridge and with limited control on the underlying traffic model. OBrien et al. [26] use a car-following model to identify critical traffic conditions for long-span bridge loading. They find that the widely-used full-stop condition is not always the critical loading case, depending on span length and truck percentage. However, only single-lane traffic is considered in that study, as well as only one traffic inflow value. In this paper, a similar micro-simulation approach is extended to multiple lanes by incorporating a lane-changing model and considering several traffic inflows, which enables the study of long-span bridge loading under a variety of traffic conditions.

### 1.1. Data collection and analysis

Nowadays, traffic weight data is typically based on weigh-in-motion (WIM) measurements. However, many WIM sensors cannot weigh vehicles accurately at slow speeds. Furthermore, data on vehicle speeds and inter-vehicle gaps is mostly collected using point detectors, such as *induction loops* (sometimes combined with WIM sensors), which also may not be reliable at low speeds [27]. As a consequence, and because congestion may be uncommon, there is a shortage of data about slow-moving – and therefore closely-spaced – vehicles, leading to the fact that most long-span bridge loading studies make conservative assumptions about vehicle spacing. Moreover, even the analysis of the collected congested traffic data can cause some problems [28,29]. In fact, vehicle positions can only be estimated from point measurements – typically under an assumption of constant speed that may not hold during congestion – and this is likely to result in a loss of accuracy when estimating the maximum number of vehicles present on a bridge. This inaccuracy is clearly reflected on the bridge loading estimates [30]. In theory, the use of cameras over a stretch of road would provide accurate information on vehicle positions. However, there are practical issues which make a camera-based approach difficult, such as sensitivity to weather and lighting conditions and heavy post-processing requirements [27]. Cameras have however been deployed for research purposes [31–35] and are becoming increasingly popular. In bridge-related studies, only a few studies report that cameras were used to collect traffic data [14,16,25,36–38].

When overtaking is allowed, the car–truck mix for congestion is expected to be different to that for free traffic, since car drivers do not feel comfortable following trucks as the general traffic speed slows and therefore tend to overtake them [39]. This typically results in longer truck-only platoons in congested traffic than in free-flowing conditions. Unfortunately, data collection is even more problematic when studying lane-changing manoeuvres, since several vehicles are involved in each manoeuvre. In such cases, cameras become necessary to track the vehicle manoeuvres.

### 1.2. Lane-changing

Lane-changing manoeuvres are traditionally divided into *discretionary* and *mandatory*. Mandatory lane changes are performed in order to follow a specific path (for instance in presence of on- or off-ramps), while discretionary lane changes are performed because of a perceived advantage in the target lane [40]. In this work, the focus is on discretionary lane changes.

Sparmann [41] observes and computes lane change frequencies over a 1 km stretch of road on the A5 Autobahn near Karlsruhe (Germany). He finds that, with increasing flow, the *lane change rate* (number of performed lane changes per kilometre and per hour) increases up to about 600 LC/km/h at about 2000 veh/h. Then the rate decreases to approximately 400 LC/km/h at 3000 veh/h. There is also some limited data about lane changes during congestion. In this case, lane change rates are substantially less than in free traffic. He states that there is a very slight decreasing relation between the lane change rate and the proportion of trucks, but no details are given.

Yousif and Hunt [42] observe lane change frequency and lane utilisation on the M4 motorway and two dual carriageways in the United Kingdom. They find that the lane change rate has a peak of 600 LC/km/h at about 2000 veh/h and then decreases to about 300 LC/km/h at 3000 veh/h. The average percentage of truck traffic is 20%, but no analysis of truck influence is performed. They also analyse a 3-lane section of the M4 and find a similar lane change rate trend with a peak of about 1100 LC/km/h at 3000 veh/h.

McDonald et al. [43] analyse the lane usage and lane changes on several 3-lane motorways in the United Kingdom. They find quite a constant lane change rate, unlike the studies of Sparmann [41] and Yousif and Hunt [42]. However, their flow range is limited compared to the other two studies and roughly centred on the expected peak at 3000 veh/h. They also state that lane change rates appear to be independent of the heavy vehicle percentage (which is at most 24%).

More recently, Knoop et al. [44] analyse data from the 3-lane M42 motorway (UK). They find a similar trend in lane change rates with a peak of 1300 LC/km/h. Interestingly, they use other parameters to quantify lane changes, instead of the usual lane change rate. They find that one lane change occurs for every kilometre of road travelled (LC/veh-km) in very light traffic conditions to 0.5 LC/veh-km, as traffic approaches capacity. In a further paper, Knoop et al. [45] analyse video data from a 2-lane motorway in the Netherlands. In this case, they find that 0.4–0.5 lane changes occur for every km travelled. The difference from the M42 dataset is stated to be due to differences in road layout, which led to mandatory lane changes.

The Federal Highway Administration [34] has made available about 90 min of trajectory data of congested traffic from two freeways in the United States. The lane change rates that can be deduced are rather high [46,47]. However, they suffer from a complex multi-lane layout with on- and off-ramps, which may include mandatory lane changes, as well as from detection issues [48–50].

In all the above papers, there is no data about lane change rates in congested conditions, except for a few points by Sparmann [41]. Moreover, there is no analysis of the lane changes performed by trucks. Moridpour et al. [51] show that there are differences between the lane-changing behaviour of heavy vehicles and passenger cars under congestion. However, the dataset is taken from the Federal Highway Administration [34], which is too small to base general conclusions. No study of truck lane change rates is performed, but it can be deduced that, on average, a truck performs 0.21 lane changes for every km travelled.

In the bridge loading field, Hayrapetova [52] analyses the lane changes occurring in one day over a 3-lane motorway bridge in the Netherlands. She observes a trend similar to other studies and indicates that about 10% of the lane changes are performed by trucks. However, no analysis of either car or truck lane change rates is reported.