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Effect of single-lane congestions on long-span bridge traffic loading

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ABSTRACT: It is well known that traffic loading of long-span bridges is governed by congestion. In spite of the fact that field observations in the past decades have shown that congestion can take up different forms, most previous studies on bridge traffic loading consider only a queue of standstill vehicles. In this paper, a micro-simulation tool is used for generating congested traffic on a single-lane roadway. The underlying micro-simulation model has been found capable of successfully replicating observed congestion patterns on motorways by simulating single-lane traffic with identical vehicles. Here trucks are introduced into the model, in an investigation of the total load for a 200 m span bridge. Different congestion patterns are found and studied in relation to their effect on loading. It is found that the bumper-to-bumper queue is not necessarily the most critical situation for the sample long-span bridge, since it does not allow the flowing of vehicles and therefore decreases the probability of observing critical loading events. Slow-moving traffic, corresponding to heavy congestion, can be more critical, depending on the truck proportion.

KEY WORDS: Long-span; bridge; traffic; loading; micro-simulation; congestion.

1 INTRODUCTION

1.1 Motivation

It is generally acknowledged that short span bridges are governed by small numbers of vehicles in free flowing traffic, with an allowance for dynamic amplification. On the other hand, bridges with span longer than about 50 m are governed by congested conditions, when a great number of vehicles are present at much closer spacing. In the latter case, no allowance for dynamics is appropriate.

Traffic loading for long-span bridges is not taken into account in most codes, due to their relatively low number. Common design practice for traffic loading on long-span bridges relies on conservative assumptions about the traffic and does not consider the variability of congestion patterns and driver behaviour. This has important implications for the assessment of existing bridges as it could make the difference between performing rehabilitation or not. Maintenance operations for long-span bridges are expensive and conservative assumptions may play a decisive role, resulting in unnecessary expenditure and traffic disruption.

1.2 Available models

The available models for traffic loading on long-span bridges take into account the variability of truck weights, but they often assume a mix of cars and heavy vehicles at a minimum bumper-to-bumper distance [1-6].

Truck weight data for these models comes either from traffic surveys or, more recently, from weigh-in-motion stations. Other traffic data (such as average speeds or car counts) generally comes from embedded loop detectors, which may be combined with weigh-in-motion stations. Data is very often collected during free-flowing traffic, due to the fact that it occurs more frequently than congested traffic and the sensor accuracy is generally less of a problem.

An important feature of traffic in the context of bridge loading is that drivers do not usually like staying between larger vehicles and therefore cars typically move out from between trucks, as traffic becomes congested. This results in the formation of truck platoons in the slow lane, changing the car-truck mix during congestion events. This makes the direct use of the widely available (and used) free-flowing traffic measurements problematic. Videos have been used for collecting suitable congested data for bridge loading [5, 7] but not frequently.

1.3 The use of traffic micro-simulation

Traffic micro-simulation (i.e., simulating the motion of individual vehicles) describes the interactions between vehicles, effectively generating different congestion patterns. Notably, free traffic measurement can be used as initial traffic conditions for a micro-simulation model. OBrien et al. [8] studied a heavily-congested Dutch long-span bridge and used a commercial micro-simulation tool with WIM data, videos and strain gauge measurements. Chen & Wu [9] used the cellular automata model, [10], dividing the bridge into 7.5 m cells. However, the cellular structure does not allow for the variability of vehicle lengths and gaps between vehicles.

In this paper, the car-following Intelligent Driver Model is used [11]. The flow of two classes of vehicles (cars and trucks) running on a single-lane road is studied. Two different truck percentages are considered. The different congested states are identified and the total load on a 200 m long bridge is computed. The simulations are carried out using an in-house program called Simba (Simulation for Bridge Assessment). A similar study for identical vehicles has been presented in Lipari et al. [12].
2 TRAFFIC MICRO-SIMULATION

2.1 Overview

Micro-simulation is widely used today in traffic studies. Models vary in their levels of complexity and accuracy. The so-called car-following models consider driver behaviour within a single lane, simulating the interaction between a vehicle and its leader [13, 14]. More complex lane-changing models are also available.

While macro-simulation considers only the aggregate properties of a traffic stream, micro-simulation considers the motion of individual vehicles. Aggregate properties can be extracted from micro-simulation models as well, but this may be insufficient to validate all results. Unfortunately, microscopic (individual vehicle) data is difficult to collect, with the result that microscopic models are often only calibrated at an aggregate level [15]. Suitable data for calibrating lane-changing models is even more difficult to collect, since it requires, for instance, video tracking over a long stretch of road to capture the interaction between all the vehicles involved in lane-changing manoeuvres.

2.2 The IDM car-following model

Treiber et al. [11] present the ‘Intelligent Driver Model’ (IDM), a car-following model that gives a good match, at macroscopic level, with real congested traffic from several motorways [11, 16]. It has a modest number of physically-meaningful parameters and has been also calibrated with real trajectory data [17-19]. Results from the calibrated IDM are comparable with more complex models [20, 21].

The IDM is implemented for this study in the Simha program. The motion is simulated through an acceleration function:

\[
\frac{dv}{dt} = a \left[ 1 - \left( \frac{v(t)}{v_0} \right)^4 - \left( \frac{s^*(t)}{s(t)} \right)^2 \right]
\]

where \( a \) is the maximum acceleration, \( v_0 \) is the desired speed, \( v(t) \) is the current speed, \( s(t) \) is the current gap to the vehicle in front, and \( s^*(t) \) is the minimum desired gap, given by:

\[
s^*(t) = s_0 + T v(t) + \frac{v(t) \Delta v(t)}{2 \sqrt{a b}}
\]

In Equation (2), the term \( s_0 \) is the minimum bumper-to-bumper distance, \( T \) is the safe time headway, \( \Delta v(t) \) is the speed difference between the current vehicle and the vehicle in front, and \( b \) is the comfortable deceleration. An advantage of this approach is that just five measureable parameters are sufficient to capture driver behaviour.

The length of vehicles must be known as well. A simulation step of 250 ms is used for discretising the system with Equations (1) and (2). The IDM can be extended to multi-lane simulation with the lane-changing model MOBIL [22].

3 CONGESTED TRAFFIC STATES

3.1 Inducing congestion

Congestion can be easily generated by applying flow-conserving inhomogeneities [11]. This is achieved through a local variation of the parameters. For example, the desired speed, \( v_0 \), is decreased or the safe time headway, \( T \), is increased downstream. These changes have a similar effect as an on-ramp bottleneck or a lane closure. This approach has been successfully applied to single-lane and identical vehicle simulations for simulating congested traffic observed on some multi-lane German and Dutch motorways [11].

In this paper, inhomogeneity is generated by increasing the safe time headway, \( T \), to a new level, \( T' \), downstream from where the congestion is sought. Treiber et al. [11] suggest that this is more effective than decreasing \( v_0 \).

The bottleneck strength, \( \Delta Q \), is a measure of the strength of the congestion-inducing phenomenon. It is defined as the difference between the outflow, \( Q_{out} \), with the original parameter set and the outflow, \( Q'_{out} \), with the modified set, in this case with the modified safe time headway \( T' \):

\[
\Delta Q(T') = Q_{out}(T) - Q'_{out}(T')
\]

Treiber et al. [11] refer to the outflow \( Q_{out} \) as the dynamic capacity, i.e., the outflow from a congested state. It is less than the static capacity \( Q_{max} \), which is only achieved in free equilibrium traffic.

Table 1 lists six alternative forms of congestion [11, 23]. The traffic can take up any of these states, depending on the combination of inflow \( Q_{in} \) and bottleneck strength \( \Delta Q \). Combinations of these congested states are also possible and previous traffic history can influence the state of congestion.

Table 1. Definition of traffic states.

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Explanation of traffic state</th>
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<tbody>
<tr>
<td>FT</td>
<td>Free traffic</td>
</tr>
<tr>
<td>MLC</td>
<td>Moving localized cluster</td>
</tr>
<tr>
<td>PLC</td>
<td>Pinned localized cluster</td>
</tr>
<tr>
<td>SGW</td>
<td>Stop and go waves</td>
</tr>
<tr>
<td>OCT</td>
<td>Oscillatory congested traffic</td>
</tr>
<tr>
<td>HCT</td>
<td>Homogeneous congested traffic</td>
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</table>

3.2 Dynamic capacity of multi-class traffic

The work of Treiber et al. [11] is based on identical vehicles. In order to make meaningful comparisons between traffic congestions with different truck percentages, it is necessary to appropriately scale the variables that govern the congestion.

It is well known that the capacity of a road reduces as truck proportion increases. The Highway Capacity Manual (HCM) [24] uses passenger car equivalents \( f_{pc} \) in order to scale mixed traffic to an equivalent reference flow made up of only passenger cars. For the purposes of this paper, it seems appropriate to set out an equivalence in terms of the dynamic capacity \( Q_{out} \), since this is a key parameter in predicting the congested states [11, 23, 25] and it is the one that characterises the bottleneck properties through Equation (3). Unfortunately, the dynamic capacity \( Q_{out}(T) \) is not straightforward to calculate. In fact, it is necessary to induce congestion without modifying the original parameter set (Table 3), and therefore inhomogeneities cannot be introduced.

Here the outflow is worked out by creating an overflow, i.e., by injecting a number of vehicles higher than the road capacity \( Q_{max}(T) \). Doing so leads to the formation of localized
vehicle clusters. The outflow from those clusters is deemed to be dynamic outflow $Q_{out}(T)$.

Table 2 gives the outflow from mixed traffic conditions. The reference condition 0\% and the 100\% trucks are included for comparison.

Table 2. Dynamic capacity for multi-class traffic.

<table>
<thead>
<tr>
<th>Truck percentage</th>
<th>$Q_{out}$ (veh/h)</th>
<th>$f_{in}$</th>
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<tbody>
<tr>
<td>0%</td>
<td>1686</td>
<td>1.00</td>
</tr>
<tr>
<td>20%</td>
<td>1590</td>
<td>0.94</td>
</tr>
<tr>
<td>50%</td>
<td>1462</td>
<td>0.87</td>
</tr>
<tr>
<td>100%</td>
<td>1291</td>
<td>0.77</td>
</tr>
</tbody>
</table>

4 MODEL AND SIMULATION PARAMETERS

4.1 Traffic stream

For this study, the vehicle stream is made up of two vehicle classes: cars and trucks. The parameters for each class are shown in Table 3. The car-following parameters are based on those used in [11]. Trucks have a smaller desired speed and are longer. All the parameters are constant, except for the truck gross vehicle weight (GVW), which is normally distributed with a coefficient of variation (CoV) of 0.1.

Table 3 - Model parameters of IDM

<table>
<thead>
<tr>
<th></th>
<th>Cars</th>
<th>Trucks</th>
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</thead>
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<tr>
<td>Desired speed, $v_0$</td>
<td>120 km/h</td>
<td>80 km/h</td>
</tr>
<tr>
<td>Safe time headway, $T$</td>
<td>1.6 s</td>
<td>1.6 s</td>
</tr>
<tr>
<td>Maximum acceleration, $a$</td>
<td>0.73 m/s²</td>
<td>0.73 m/s²</td>
</tr>
<tr>
<td>Comfortable deceleration, $b$</td>
<td>1.67 m/s²</td>
<td>1.67 m/s²</td>
</tr>
<tr>
<td>Minimum jam distance, $s_j$</td>
<td>2 m</td>
<td>2 m</td>
</tr>
<tr>
<td>Vehicle length, $l$</td>
<td>4 m</td>
<td>12 m</td>
</tr>
<tr>
<td>Gross Vehicle Weight</td>
<td>20 kN</td>
<td>432 kN*</td>
</tr>
</tbody>
</table>

* Normally distributed with CoV = 0.1

20\% and 50\% of trucks are randomly injected between cars in the slow lane. 20\% is a typical truck proportion on a busy highway, while the 50\% trucks accounts for the phenomenon of truck platoons in multi-lane roadways, which leads to a greater truck percentage in the slow lane. Significantly, the lane change rate is low during congestion [26], thus making the present single-lane approach suitable for multi-lane roadways as well. Indeed truck platoon formation is most likely to occur while approaching the congestion front when there are still available gaps for lane-changes.

A standard truck configuration with GVW taken as the common European highway maximum of 44 t was assumed as the mean (Figure 1). The distribution of weights between axles is based on WIM data from a French motorway [27]. Front and back overhangs of 0.9 m are also assumed.

4.2 Road geometry and bottleneck strengths

A single-lane 5000 m long road is considered. Inflows $Q_{in}$ equal to the dynamic capacities $Q_{out}$, are considered for the two truck percentages selected (see Table 2). Such inflows are deemed equivalent in terms of expected congested states, so that $Q_{in, eq} = Q_{out, eq} = 1686$ pceq/h (passenger car equivalents per hour).

From 0 to 2700 m the safe time headway is $T$ (see Table 3), then it increases linearly to 3300 m until it reaches the value $T'$. Five different values of $T'$ (1.9, 2.2, 2.8, 4.0, and 6.4 s) are considered for the simulations, each of which is 1 hour long. These values are chosen in order to generate a wide range of congestion types.

For each pair of $T'$ and truck percentage, twenty-five one-hour simulations are carried out, in order to account for the randomness involved in the truck injection and weight. Figure 2 shows the relation between the applied inhomogeneity $\Delta T = T' - T$ and the resulting equivalent bottleneck strength $\Delta Q_{eq}$.

![Figure 1. Assumed truck configuration.](image1)

![Figure 2. Equivalent bottleneck strength.](image2)

It can be seen from Figure 2 that the same inhomogeneity, $\Delta T$ returns similar equivalent bottleneck strengths $\Delta Q_{eq}$ regardless of the percentage of trucks. For further comparison with the available traffic loading models, the full stop condition is also simulated (FS). It corresponds to infinite $\Delta T$ or $Q_{out, eq} = 0$ pceq/h. Then $\Delta Q_{eq} = 1686$ pceq/h, according to Equation (3). Again, twenty-five simulations are carried out for each truck percentage. On the whole, 300 hours of simulations are run and analysed.
TRAFFIC RESULTS

5.1 Typical spatio-temporal congestion patterns

Spatio-temporal plots are useful for a global view of the congestion over time and space. The speed axis is plotted upside down, so that peaks represent congestion. Figure 3 shows a typical spatio-temporal plot for the SGW state, resulting from a light bottleneck strength.

![Figure 3. Typical SGW state (ΔQ_{eq} = 181 pceq/h, 20% trucks).](image)

As bottleneck strength increases, the oscillations reduce. Figure 4 shows a combined HCT/OCT state, where traffic is homogeneously slow near the inhomogeneity, while it is more oscillating upstream.

![Figure 4. Typical HCT/OCT state (ΔQ_{eq} = 603 pceq/h, 20% trucks).](image)

As bottleneck strength increases further, the congestion gets more homogeneous, finally reaching the HCT state throughout.

5.2 Effect of truck proportion

After having set a passenger car equivalent for the different traffic compositions analysed, it is interesting to see how different the congested states are in relation to the different truck percentages. It is convenient to draw a comparison in terms of average speed over the congested space-time domain, since both flow and density would vary depending on the truck percentage.

![Figure 5. Average congested speed.](image)

The generated congested states are actually similar, showing small differences in the average speed in the congested area (Figure 5). The case of traffic with no trucks is illustrated as a reference. The mean speed drops down to 5 km/h for the highest bottleneck strength, which represents very heavy congestion.

![Figure 6. Coefficient of variation of congested speed.](image)

As bottleneck strength increases, the oscillations reduce. Figure 4 shows a combined HCT/OCT state, where traffic is homogeneously slow near the inhomogeneity, while it is more oscillating upstream.

![Figure 6. Coefficient of variation of congested speed.](image)

LOAD EFFECT RESULTS

6.1 Introduction

In this section the load effects induced by the different congested traffic states on a sample bridge are studied to identify the most critical congestion states for bridge loading. A 200 m long single-lane bridge is placed from location 1900 to 2100 m. For each one-hour simulation, the maximum total load on the bridge is computed.

For the purpose of comparison, by assuming no cars, minimum bumper-to-bumper distance and truck average GVW, the total load on the bridge is 6048 kN (14 trucks).
6.2 20% trucks

Figure 7 shows the total load on the bridge against the bottleneck strength for the case of 20% trucks. It can be seen that the load effect increases approximately linearly until the HCT point corresponding to $\Delta Q = 1132$ pceq/h. Then, the maximum hourly load decreases as it approaches the full stop point ($\Delta Q_{\text{eq}} = 1686$ pceq/h). Notably, the average maximum hourly load corresponding to full stop is of the same order of magnitude as the lightest congestion. However, the hourly load at full stop shows a significant scatter.

The finding that full stop is not the critical loading case is significant, since most previous load models assumed this condition. Such a finding can be explained by considering that, the heavier the congestion, the slower the speed and the closer the vehicles. On the one hand, heavy congestion results in greater load effects (since vehicles are more closely spaced), but on the other, fewer vehicles have the chance to cross the bridge and the probability of having a high number of heavily overloaded trucks decreases. This explains also the wide scattering in the hourly maxima at full stop.

6.3 50% trucks

For the higher truck percentage, the results are shown in Figure 8. The full stop load has, on average, the same order of the slow moving traffic HCT. Again, it shows a higher variation about the average value, relative to the other congested states.

From the results presented it is clear that it may be non-conservative to assume the full stop condition as the most critical for bridge loading. For the 20% truck percentage, the heavy-congested and slow-moving HCT state is clearly the most critical one for the bridge considered, while differences are less when the truck percentage is higher. Figure 9 gives the average values for the two different traffic compositions.

6.4 Summary

The finding that full stop is not the critical loading case is significant, since most previous load models assumed this condition. Such a finding can be explained by considering that, the heavier the congestion, the slower the speed and the closer the vehicles. On the one hand, heavy congestion results in greater load effects (since vehicles are more closely spaced), but on the other, fewer vehicles have the chance to cross the bridge and the probability of having a high number of heavily overloaded trucks decreases. This explains also the wide scattering in the hourly maxima at full stop.

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From the results presented it is clear that it may be non-conservative to assume the full stop condition as the most critical for bridge loading. For the 20% truck percentage, the heavy-congested and slow-moving HCT state is clearly the most critical one for the bridge considered, while differences are less when the truck percentage is higher. Figure 9 gives the average values for the two different traffic compositions.

Furthermore, it is noted that a greater truck percentage reduces the variation between hourly maxima (Figure 10). Finally, the full stop condition has a significantly greater coefficient of variation, since for every one-hour simulation, there is only one possible configuration of vehicles.

7 CONCLUSIONS

This paper investigates the effect of different congestion patterns on the total load of a sample single-lane long-span bridge, using a micro-simulation tool. Previous load models neglect congestion patterns, assuming a queue of vehicles at minimum bumper-to-bumper distances. The car-following model used here has been shown to reproduce observed congestion patterns, using identical vehicles. Here we extend the use of this model to multi-vehicle-class simulations, necessary to investigate the load effects on a sample bridge.

We show that the bumper-to-bumper queue is not necessarily the most critical situation for the sample long-span bridge, since it does not allow the flowing of vehicles and therefore decreases the probability of observing critical
loading events. Indeed slow-moving traffic, corresponding to heavy congestion, are more critical states for the bridge. In this case, speeds are low enough (order of 5 km/h) to have the vehicles closely spaced, but it still allows the turnover of vehicles and the sampling of a greater number of truck combinations. This is especially valid for typical proportions of trucks, while the difference is less sharp for very high truck percentages, which may occur in the slow lane of a multi-lane highway.

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