



Title	The effect of controlling heavy vehicle gaps on long-span bridge loading
Authors(s)	Caprani, Colin C., O'Brien, Eugene J., Lipari, Alessandro
Publication date	2013-01
Publication information	Caprani, Colin C., Eugene J. O'Brien, and Alessandro Lipari. "The Effect of Controlling Heavy Vehicle Gaps on Long-Span Bridge Loading." Transportation Research Board, January 2013.
Conference details	Transport Research Board Annual Meeting, January 2013
Publisher	Transportation Research Board
Item record/more information	http://hdl.handle.net/10197/9236

Downloaded 2026-04-30 12:46:58

The UCD community has made this article openly available. Please share how this access benefits you. Your story matters! (@ucd_oa)



© Some rights reserved. For more information

THE EFFECT OF CONTROLLING HEAVY VEHICLE GAPS ON LONG-SPAN BRIDGE LOADING

Authors:

Colin C. Caprani, Dublin Institute of Technology, Department of Civil and Structural Engineering, Bolton Street, Dublin 1 (Ireland); phone number: +353 1 402 2993; fax number: +353 1 402 3720; email: colin.caprani@dit.ie

Eugene J. OBrien, University College Dublin, School of Civil, Structural and Environmental Engineering, Newstead Building, Belfield, Dublin 4 (Ireland); phone number: +353 1 716 3224; fax number: +353 1 716 3297; email: eugene.obrien@ucd.ie

Alessandro Lipari, University College Dublin, School of Civil, Structural and Environmental Engineering, Newstead Building, Belfield, Dublin 4 (Ireland); phone number: +353 1 716 3233; fax number: +353 1 716 3297; email: alessandro.lipari@ucd.ie (corresponding author)

Submission date: 1 August 2012

Word count: 6624 (4124 text, 7 figures, 3 tables)

ABSTRACT

Long-span road bridges are governed by congested traffic rather than free-flowing conditions. During congestions, heavy vehicles can get quite close to each other, thus giving potential critical loading events for the bridge.

In this paper, the effects of a system capable of warning truck drivers when the gap falls below a certain threshold are investigated. The effects are studied both in terms of increase in traffic disruption and reduction in loading. The minimum distance between trucks should be ideally adjusted in relation to the site-specific traffic features and to the load the bridge is able to carry in safety. Doing so, it is possible to allow for future increase in truck weight regulations and/or heavy traffic volumes, by adjusting the control gap value.

Importantly, the system does not presume any restriction to the truck weight. By contrast, the system is meant to be an alternative way of limiting the load on long-span bridges by keeping the trucks apart, rather than by limiting the truck weight.

The introduction of such a gap control system is studied by means of micro-simulation. The car-following model used here has been shown able to replicate many observed congestion patterns. Results show that the introduction of the gap control system does not significantly disrupt the traffic further. On the other hand, having only 10% of equipped trucks beneficially reduces the total traffic loading by about 10%. When most trucks are equipped, nearly 50% reduction in the total load can be attained.

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 queues of closely spaced vehicles. In congested conditions, vehicle-bridge dynamic interaction is not significant, since critical events occur at slow speeds. The bridge length threshold between the two cases depends on many factors but it typically lies between 30 and 50 m (2-4).

During congestions, heavy vehicles can get quite close to each other, thus giving potential critical loading events for the bridge. If such a distance could be limited, there will be fewer needs of restricting a bridge to trucks or posting a weight limit, as there will always be a maximum number of trucks on the bridge, even during congestions. Moreover, a single over-loaded trucks do not generally produce a critical event for a long-span bridge.

The minimum distance should be ideally adjusted in relation to the site-specific traffic features and to the load the bridge is able to carry in safety. The minimum distance can also allow for future increase in truck weights and/or heavy traffic volumes (or even bridge deterioration).

Current regulations about gaps between vehicles are mainly concerned about safety requirements to prevent crashes. They are usually expressed in terms of safe time gap (for instance the well-known *2-second rule*), which can be obviously adapted to any speed. However, for bridges it is important to keep the load apart and so a space gap is of interest, rather than a time gap. Some European countries prescribe a minimum distance of 50 m for trucks (Austria and Germany), or for vehicles when following heavy vehicles (France) (5). In Australia, heavy vehicle drivers must follow another HGV at a minimum of 60 m in single-lane roads (6). However, it is very difficult to enforce these limits.

In this paper, we assume that different percentages of trucks are equipped with a device that is capable of warning drivers whenever the gap falls below a certain threshold (which is a safe distance for bridge loading). Such a device can operate in the area preceding a bridge. Violation of this limit may be also enforced and fined. Furthermore, progress in *Adaptive Cruise Control* (ACC) (7, 8) may also *prevents* truck drivers from getting too close to the following vehicle.

Here we show how the implementation of such a system can beneficially reduce the load on a sample long-span bridge and study the implications on traffic congestions. The task is carried out by means of single-lane micro-simulation, which is a powerful tool to replicate and analyse congested scenarios.

Previous research on long-span bridge loading

It must be noted that traffic loading for long-span bridges is not taken into account in most notional codes, both for design of new bridges and assessment of existing bridges.

Eurocode 1 (9) gives provisions only for the design of bridges up to 200 m. The Highways Agency (10) prescribes a reduction factor of the design load model for long-span bridge assessment in the United Kingdom.

The American code gives no indication of maximum span length for application of its design load model (11), although in its calibration the maximum span considered is 60 m (12). For bridge evaluation, the American Association of State Highway and Transportation Officials (13) prescribes the use of a *legal* load model for the rating of existing bridges longer than 60 m.

Traffic loading models developed for short-span bridges are usually rather conservative when applied to longer spans, as long decks are hardly ever filled up with heavy vehicles. Moreover, the observed different congestion types are usually neglected, as most models assume a mix of cars and heavy vehicles at a minimum bumper-to-bumper distance (1, 14-19).

Finally, calibration and validation of traffic congested load models face a lack of data, as weigh-in-motion stations and common traffic measurements, such as induction loops, may not be reliable at very low speeds (20). As a consequence, data is generally collected during free-flowing traffic conditions, which also occur more frequently than congestions.

MICRO-SIMULATION

Micro-simulation is widely used in traffic engineering with many models having been developed in the past decades (21-23). Micro-simulation takes account of the interaction between vehicles, thus introducing driver behaviour into the model. Free traffic measurements can still be used to generate initial traffic conditions, although congested data is still required for calibration and validation (24).

In the bridge loading field, OBrien et al. (25) studied a long-span bridge in the Netherlands and calibrated a commercial micro-simulation tool using WIM data, videos and strain gauge measurements. Caprani (26) used micro-simulation to calibrate a simple congested load model for short- to medium-length bridges.

Chen and Wu (27) used the cellular automaton approach (initially proposed by Nagel and Schreckenberg (28)), in which the bridge is divided into 7.5 m cell. However, the cellular structure does not allow for the variability of vehicle lengths and gaps between vehicles.

In this paper, a micro-simulation model is used which has been found to replicate many kinds of observed congestion on several motorways (29). The micro-simulation approach has been programmed in-house and the program is known as SIMBA (SIMulation for Bridge Assessment). The focus here is to preliminary assess the impact of a system that warn truck drivers when not keeping a set minimum distance to the front vehicle.

Single-lane micro-simulations are carried out considering a high inflow rate, representative of peak hour traffic. Truck percentage is set to 20%, which is typical of a busy highway. Different percentages of trucks are equipped with the gap control system. Two different congestion types are generated and the total load is studied on a 200 m span.

The Intelligent Driver Model

Micro-simulation models divide into car-following (single-lane) and lane-changing (multi-lane) models. The Intelligent Driver Model (IDM) is a car-following model, which, in spite of having few parameters, has been shown to provide a good match with real congested traffic on some German *multi-lane* motorways (29). It has also been calibrated with trajectory data (30-32) and compared to other calibrated car-following models, returning results comparable to more complex models (33, 34). It is considered by the authors to be an optimal compromise between accuracy and computational speed.

The IDM simulates driver behaviour in time through an acceleration function:

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

where a is the *maximum acceleration*; v_0 , the *desired speed*; $v(t)$, the current speed; $s(t)$, the current gap to the front vehicle and; $s^*(t)$, the *desired minimum gap*. The motion results from the interaction of a deceleration and an acceleration strategy. The term $dv/dt = -a(s^*(t)/s(t))^2$ represents the tendency to brake when a vehicle gets too close to the leader, whereas the remaining term of Equation (1) represents the tendency to accelerate on a free road.

The *desired minimum gap* s^* in Equation (1) is given by:

$$s^*(t) = s_0 + Tv(t) + \frac{v(t)\Delta v(t)}{2\sqrt{ab}} \quad (2)$$

in which, s_0 is the *minimum bumper-to-bumper distance*; T , the *safe time headway*; $\Delta v(t)$, the speed difference between the current vehicle and the vehicle in front, and; b , the *comfortable deceleration*. Equations (1) and (2) are discretised here into 0.25 s steps.

There are five parameters in this model to capture driver behaviour, which are relatively easy to measure. For simulation purposes, the length of the vehicles must also be known.

Congested Traffic States

Treiber et al. (29) showed that congestion can be effectively generated by either locally decreasing the desired speed v_0 or increasing the safe time headway T (*flow-conserving inhomogeneity*). Such local parameter variations slow the traffic in a similar way to on-ramp bottlenecks or lane-closures. In this paper, inhomogeneity is generated by increasing the safe time headway T downstream, say T' , which Treiber et al. (29) state to be more effective than decreasing v_0 .

A *bottleneck strength* ΔQ can be defined as the difference between the outflow Q_{out} with the original parameter set and the outflow Q'_{out} with the modified safe time headway T' .

$$\Delta Q(T') = Q_{out}(T) - Q'_{out}(T') \quad (3)$$

The outflow here is the *dynamic capacity*, that is, the outflow from a congested state. It is well known that, after traffic flow breaks down, the maximum outflow drops from the static capacity Q_{max} to a value related to the discharge rate of the queue (35-37). For practical applications, the velocity at the detector nearest to the bottleneck can also be used as a proxy for the bottleneck strength (38).

Depending on the inflow Q_{in} and the bottleneck strength ΔQ , the downstream traffic can take up any of the identifiable traffic states explained in Table 1 (29, 39). The traffic history may also affect the expected congested state.

In general, increasing inflow and/or bottleneck strength has the effect of moving down the table to a higher intensity of congestion. A combination of these congested states may also occur (the most common is the combined HCT/OCT state). Congested states that occupy a significantly long stretch of road (*extended* states), such as SGW, OCT and HCT, are of significance for long-span

bridge loading applications. In general, increasing bottleneck strength has the effect of increasing the total load on a bridge, whereas the inflow plays a minor role, as long as it is high enough to trigger congestion (40).

TABLE 1 – Congested traffic states

Acronym	Explanation of traffic state
FT	Free traffic
MLC	Moving localized cluster
PLC	Pinned localized cluster
SGW	Stop and go waves
OCT	Oscillatory congested traffic
HCT	Homogeneous congested traffic

Implementation of the control gap

The *control gap* g^* produces an additional inhomogeneity in the traffic stream, effectively decreasing the vehicular density in the controlled area. A modification in the motion equation (1) must be introduced for trucks equipped with the control gap device, so that truck drivers tend to keep a gap reasonably close to the control gap. Importantly, such a gap must be independent of the speed. Caprani (41) modified the safe time headway T with partially satisfactory results (as the modification would not be independent on the speed). It is also apparent that a simple modification of the minimum bumper-to-bumper distance s_0 cannot give the expected results, as it will equally increase the desired minimum gap s^* at any speed.

Several tests have been performed to find the most suitable modification to implement the control gap g^* . Here, we report three selected possible solutions tested:

1. the term $s_0 + Tv(t)$ in Equation (2) is limited to be equal or greater than g^* ;
2. the desired minimum gap s^* in Equation (2) is limited to be equal or greater than g^* ;
3. a truck behaves as if its follower were closer than it is; in other words the current gap in Equation (1) is reduced to $s(t) = s_{\text{actual}}(t) - (g^* - Tv(t))$.

In fact, the capping of the desired minimum gap s^* (solutions 1 and 2) may not suffice to ensure that that control gap g^* is respected, as the acceleration depends also on the speed ratio and a vehicle tends to brake when the gap s is equal to s^* (Equation 1). In solution 3, the control gap is then diminished by the safe distance $Tv(t)$, which is the distance a truck would keep anyway when following a vehicle.

Figure 1 shows a truck going at 80 km/h while approaching a truck going at 50 km/h. The initial gap is 100 m and the control gap is 50 m. It can be seen that solutions 1 and 3 make the truck keep the gap a bit higher than the control gap, which is desirable, whereas solution 2 makes the truck speed oscillate around the control gap (Figure 1a). The deceleration rates of solutions 1 and 3 are also quite smooth and similar (Figure 1b).

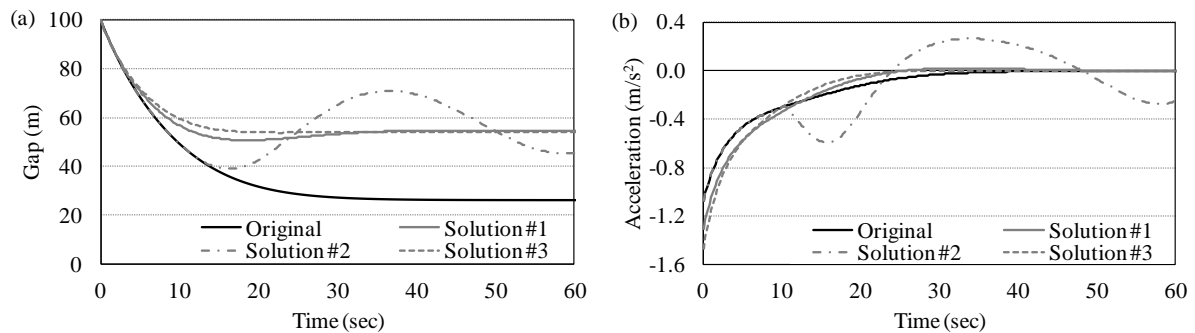


Figure 1. Gap (a) and acceleration (b) of a truck approaching a slower vehicle.

However, when considering a truck going at 50 km/h and approaching an obstacle positioned at 100 m, results are slightly different. The original formulation would make the truck stop at a gap very close to the minimum bumper-to-bumper distance s_0 . Figure 2a shows that solutions 1 and 2 make the truck overshoot at a gap much closer than it should, while solution 3 makes the truck stop at a value reasonably close to the 50 m control gap. This of course comes at cost of a stronger deceleration rate (Figure 2b). However, this deceleration has a single-step peak of 9 m/s^2 , while its average deceleration is about 2.5 m/s^2 , which is a reasonable deceleration rate considering that the truck is approaching a standstill object (42). The other solutions have a soft deceleration rate ($1.5\text{-}1.6 \text{ m/s}^2$), which have the order of the comfortable deceleration b .

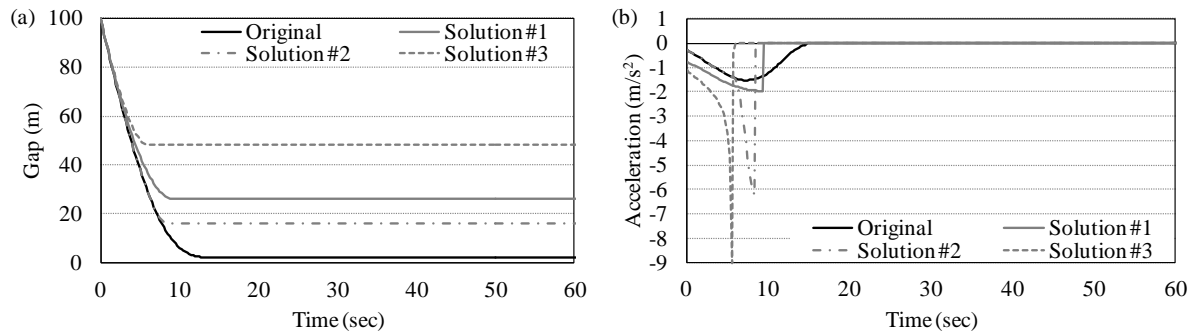


Figure 2. Gap (a) and acceleration (b) of a truck approaching an obstacle.

Therefore, solution 3 is adopted for modelling the trucks equipped with the gap control device.

MODEL AND SIMULATION PARAMETERS

Traffic stream

For this study, the vehicle stream is taken as being made up of cars and trucks. Each vehicle of the same class is given the same set of parameters, shown in Table 2. The car parameter set is based on the one used by Treiber et al. (29), while the truck parameters are chosen empirically, acknowledging that they are slower, longer, and heavier. All the parameters are taken to be constant, except for the truck gross vehicle weight (GVW), which is normally distributed with a Coefficient of Variation (CoV) of 0.1. The mean truck GVW is taken as the common European legal limit of 44 t.

We assume that 0 (*base condition*), 10, 50 and 90% of the trucks are equipped with the gap control device. The control gap is set to 20 and 50 m.

TABLE 2 - Model parameters

Parameter	Car	Truck
Desired speed, v_0	120 km/h	80 km/h
Safe time headway, T	1.6 s	1.6 s
Maximum acceleration, a	0.73 m/s^2	0.73 m/s^2
Comfortable deceleration, b	1.67 m/s^2	1.67 m/s^2
Minimum jam distance, s_0	2 m	2 m
Vehicle length, l	4 m	12 m
Gross Vehicle Weight (GVW)	20 kN	432 kN ¹

¹Normally distributed with CoV = 0.1

Road geometry and bottleneck strength

A single-lane 5000 m long road is used in this work. The safe time headway is T from 0 to 2700 m (see Table 2), then increases gradually to the value T' at 3300 m. Two values of T' are considered: 2.2 and 4.0 s, which return a reduced outflow Q'_{out} equal to 1230 and 760 veh/h.

The dynamic outflow Q_{out} is 1590 veh/h and it is found by means of simulations, as the outflow coming out of a queue. The inflow Q_{in} is set equal to the dynamic capacity, Q_{out} , so the bottleneck strengths ΔQ are 360 veh/h and 830 veh/h.

A 200 m long bridge is centred at 2000 m. The control gap area starts 1 km ahead of the bridge (at 900 m). The control gap is implemented gradually so that it simulates the adaptation of the truck driver behaviour to the control system, thus avoiding hard braking manoeuvres.

Finally, it is assumed that the road is recurrently affected by one hour of congestion each working day of a 250-day year. One year of congested traffic is simulated for each bottleneck strength, control gap and percentage of equipped vehicles, for a total of 3500 hours of congestion generated and analysed.

TRAFFIC RESULTS

Spatio-temporal congestion plots

Spatio-temporal speed plots are useful for visualizing congested patterns. They display aggregate traffic quantities in the space-time domain. Here, the *space mean speed* is used, which is the harmonic mean of the individual speeds collected at one point (43). The space mean speed is collected as one-minute averages at four virtual point detectors placed between 1000 and 2500 m. Figure 3(a) shows the congested OCT state, generated with $T' = 2.2$ s. The waves are clearly visible as peaks. Note that drivers do not recover speed between the waves, unlike the lighter SGW state. OCT states are quite frequent congested states (29, 39). Figure 3(b) shows the HCT state resulting from $T' = 4.0$ s. Small oscillations are present upstream and fade away approaching the inhomogeneity. The average speed in the congested area is about 9 km/h. This is a rarer state that usually occurs after serious incidents (39).

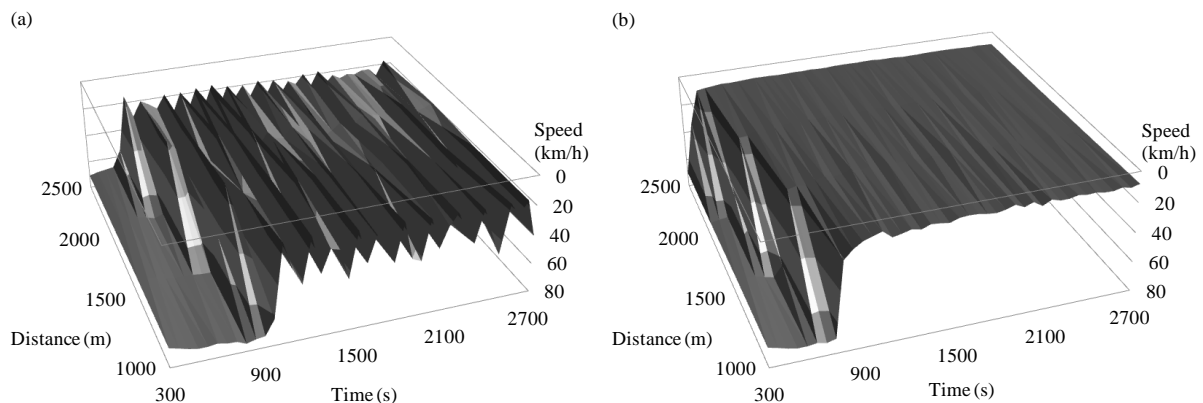


Figure 3. Spatio-temporal speed plots of OCT (a) and HCT (b).

It should be noted that smaller inflows need stronger bottlenecks to generate congestion. However, this causes the traffic to go straight to the heavy HCT states, skipping the oscillatory congested states SGW and OCT (29, 39).

Effects of the control gap

It is interesting to see how much the introduction of the control system disrupts the traffic further. Figure 4(a) compares the flow computed at a virtual detector placed at 1500 m (within the controlled area) to the flow at the same point when there are no equipped trucks (base conditions). It can be seen that the flow is decreased by less than 2%, indicating that the severity of congestion is not significantly increased by the introduction of the system.

It is also interesting to consider the traffic oscillation properties and see how they change with the introduction of the control system (Figure 4(b)). A greater coefficient of variation of the speed indicates prominent oscillatory behaviour. Indeed the lightest bottleneck strength shows a high coefficient of variation, which is not significantly changed by the control system. On the other hand, the gap control enhances the speed oscillations at the strongest bottleneck, actually changing the congestion type. This is expected because trucks need to slow down more to reach the control gap, effectively generating shockwaves.

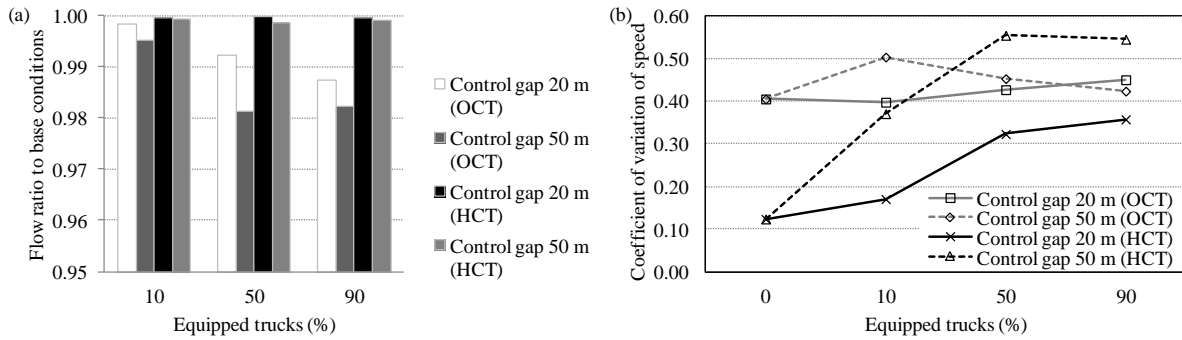


Figure 4. Flow (a) and average coefficient of variation of speed (b) in the congested area.

LOAD RESULTS

Introduction

In this section, the total load on a 200 m bridge is computed. The maximum total load for each one-hour congestion event is captured. Assuming one hour of congestion per day, the hourly/daily maximum values of the total load are extrapolated to determine 5-year characteristic values. Note that 5-year is also the representative period of time used for bridge assessment in the United States (44, 13).

Probability paper plotting is useful to visualise statistical data. The probability of non-exceedance, $F(z)$, is given on the y-axis using the standard extremal variate (the double logarithm Gumbel distribution scale, see Coles (45)). On this paper, Gumbel distribution compliant data appears as a straight line. The target probability of non-exceedance for maximum-per-day data is $1-1/1250 = 0.9992$ and its y-axis value on the probability paper is 7.13.

The Generalised Extreme Value (GEV) distribution is fitted to the simulated hourly maximum total loads. The probability F that a load level, z , is not exceeded is (45):

$$F(z) = \exp \left\{ - \left[1 + \xi \left(\frac{z - \mu}{\sigma} \right) \right]^{\frac{1}{\xi}} \right\} \quad (4)$$

where μ is the location, σ the scale and ξ the shape parameter. Equation (4) is defined for any value z for which

$$1 + \xi \left(\frac{z - \mu}{\sigma} \right) > 0 \quad (5)$$

When $\xi = 0$, the GEV distribution reduces to the Gumbel distribution. The GEV parameters are inferred through maximum likelihood estimation (for details, see Coles (45)).

Results

The probability paper plot of the base condition (no trucks equipped) is shown in Figure 5, as well as the 5-year characteristic daily maximum values z^* . It can be seen that the two congestion types are well separate from each other, with the stronger congestion returning greater total load. The distribution for the combination of congestions is also plotted and it is addressed in the next section.

Table 3 indicates that, except for one single case of compliance to the Gumbel distribution ($\xi = 0$), the curves tend upwards, suggesting compliance with the Weibull distribution ($\xi < 0$). The Weibull distribution indicates data for which there is an upper limit, i.e., there is a limiting level which is not exceeded.

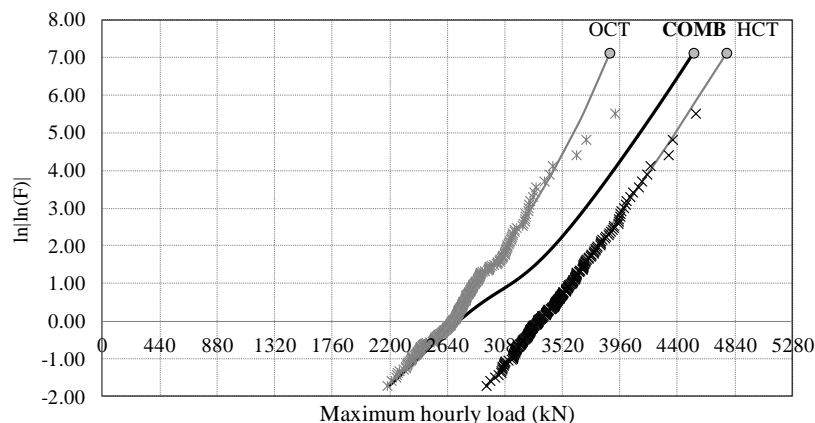


Figure 5. Probability paper plot of base conditions (no equipped trucks); each vertical gridline approximately represents one average truck.

Figure 6 shows the effect of the control gap on the 5-year total load for the two bottleneck strengths considered, indicated as ratio to the total load in base conditions. It can be seen that a percentage of 10% equipped trucks does not return a significant reduction in the lighter bottleneck. Reductions become higher at the stronger bottleneck, that is when total load is greater and therefore a reduction becomes more beneficial.

It can be also noted that at the low bottleneck strength the extrapolated load with the 50 m control gap is higher than the one with control gap 20 m. This is not due to an actual higher mean of the load, but instead to a higher curvature ζ of the 20 m extrapolation curve (see Table 3).

When the percentage of equipped trucks increases to 50%, reductions are more interesting, as the reductions in total load lie between 26 and 36%. When most trucks are equipped, reductions are more significant and the actual control gap imposed plays a bigger role (reduction can get up to 48%).

It must be noted that such reductions are attained with exactly the same traffic, that is without posing any weight restriction to trucks.

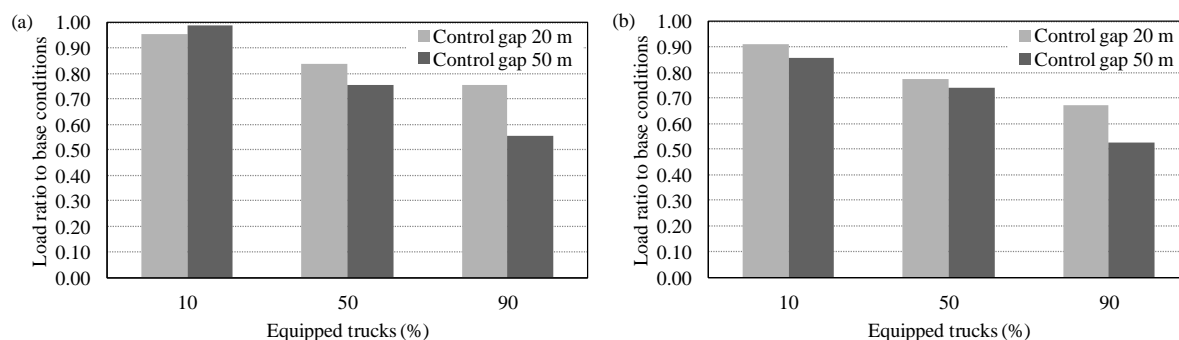


Figure 6. Ratio of the 5-year load to the base conditions for OCT (a) and HCT (b).

TABLE 3. Parameters and extrapolated values of the GEV distribution.

Equipped trucks (control gap)	OCT				HCT			
	μ	σ	ζ	z^*	μ	σ	ζ	z^*
0%	2644	247.1	-0.106	3880	3344	226.5	-0.035	4774
10% (50 m)	2490	226.4	-0.051	3845	3178	227.6	-0.181	4089
50% (50 m)	1828	216.2	-0.097	2940	2406	210.3	-0.086	3529
90% (50 m)	1461	97.7	0.000	2158	1760	144.5	-0.096	2506
10% (20 m)	2582	236.3	-0.122	3708	3244	230.7	-0.120	4350
50% (20 m)	2294	199.3	-0.118	3255	2831	193.8	-0.144	3696
90% (20 m)	2022	179.0	-0.099	2939	2334	126.5	-0.004	3222

Combination of congestions

Real world observations have shown that many types of congestion can occur. Intuitively, light forms of congestion are more frequent than strong ones. Schönhof and Helbing (39) categorised more than 240 traffic breakdowns occurred on the busy A5 motorway in Germany. The most frequent extended congestion states were SGW and OCT, whereas HCT states were typical of congestion resulting from serious accidents. According to the data reported in Schönhof and Helbing (39), we assume that the OCT congestion events (or lighter congestions) occur on 75% of the working days in one year, whereas the heavy HCT occurs on the remaining 25% working days.

It is then necessary to statistically combine the two different congestion types, either of which can occur with the assigned probabilities. This is done by applying the law of total probability. The probability P that the load does not exceed z in the reference period is:

$$P(z) = \sum_j F_j(z) \cdot f_j = F_{OCT}(z) \cdot f_{OCT} + F_{HCT}(z) \cdot f_{HCT} \quad (5)$$

where F_j is the cumulative distributive function for the maximum hourly/daily load for the j^{th} congestion type (either OCT or HCT) and f_j is the assigned probability of occurrence for that type. The target probability of non-exceedance is 0.9992.

An example of the combined distribution function $P(z)$ curve is shown in the probability paper plot of Figure 5. Equating $P(z)$ to the target probability gives the characteristic combined load level, z^* . Figure 7 shows the 5-year characteristic values, as ratio to the base condition with no equipped trucks. The reduction lies somewhat in between the two congested cases, but slightly closer to the heavier (although rarer) HCT state.

A small percentage of trucks reduces the total load by approximately 10%, which may be desirable in a first implementation phase of the system. When half of the trucks are equipped, reductions get to about 75%. Finally, the control gap value starts making a significant difference only when a large number of trucks is equipped.

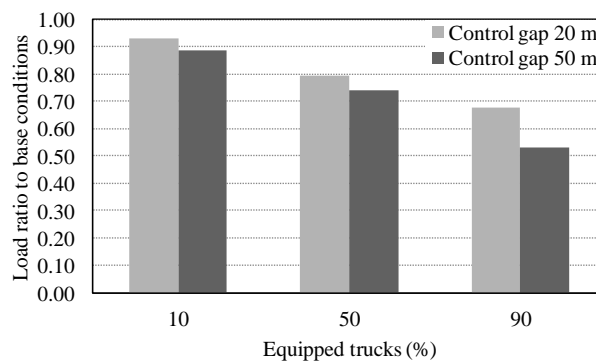


Figure 7. Comparison of characteristic total load to the base conditions.

CONCLUSIONS

This paper investigates the effects on bridge loading of a gap control device which limits the gap between a truck and its leader during congested conditions by means of traffic micro-simulation. In fact, during congestions heavy vehicles can get very close to each other, thus giving potential loading events for long-span bridges. The car-following model used here has been found able to reproduce observed congested patterns.

Results show that when only 10% trucks are equipped, it is possible to attain a 10% reduction in the total load on a 200 m span. If 90% of the trucks are equipped this reduction can be as high as 47%. On the other hand, it is found that the introduction of the system does not significantly increase the traffic disruption.

It must be emphasised that this system does not require any weight restriction to the traffic. The control gap value should be adjusted to the site-specific traffic features and to the load that the bridge is able to carry in safety, thus accounting for future increase of truck weights and/or heavy traffic volumes, or even deterioration of the bridge.

Acknowledgement

This work is part of the TEAM project (Training in European Asset Management). The TEAM project is a Marie Curie Initial Training Network and is funded by the European Commission 7th Framework Programme (PITN-GA-2009-238648).

References

- (1) Ivy, R. J., T. Y. Lin, S. Mitchell, N. C. Raab, V. J. Richey, and C. F. Scheffey. Live loading for long-span highway bridges. *American Society of Civil Engineers Transactions*, Vol. 119, 1954, pp. 981-1004.
- (2) Bruls, A., P. Croce, L. Sanpaolesi, and G. Sedlacek. ENV 1991 - Part 3 : Traffic load on bridges - Calibration of road load models for road bridges. IABSE Colloquium, Delft, 1996, pp. 439-453.
- (3) OConnor, A. J., and E. J. OBrien. Traffic load modelling and factors influencing the accuracy of predicted extremes. *Canadian Journal of Civil Engineering*, Vol. 32, No. 1, 2005, pp. 270-278.
- (4) Caprani, C. C. Lifetime highway bridge traffic load effect from a combination of traffic states allowing for dynamic amplification. *Journal of Bridge Engineering*, Vol. in print, 2012.
- (5) Conference of European Directors of Roads. *Safe distance between vehicles*. CEDR report 2009/10.1. CEDR, 2010.
- (6) Roads and Maritime Services. *Heavy vehicle driver handbook*. RMS/Pub. 07.353. Roads and Maritime Services, 2011.
- (7) Naranjo, J. E., C. González, J. Reviejo, R. García, and T. d. Pedro. Adaptive Fuzzy Control for Inter-Vehicle Gap Keeping. *IEEE Transactions on Intelligent Transportation System*, Vol. 4, No. 3, 2003, pp. 132-142.
- (8) Kesting, A., M. Treiber, and D. Helbing. Enhanced intelligent driver model to access the impact of driving strategies on traffic capacity. *Philosophical Transactions of the Royal Society A*, Vol. 368, 2010, pp. 4585-4605.
- (9) European Committee for Standardization. *Eurocode 1: Actions on Structures*. CEN, 2003.
- (10) The Highways Agency. *Design Manual for Roads and Bridges*. The Highways Agency, 2001.
- (11) American Association of State Highway and Transportation Officials. *AASHTO LFRD Bridge Design Specifications - Fifth edition*. American Association of State Highway and Transportation Officials, 2010.
- (12) Nowak, A. S. Calibration of LFRD Bridge Code. *Journal of Structural Engineering*, Vol. 121, No. 8, 1995, pp. 1245-1251.
- (13) American Association of State Highway and Transportation Officials. *The Manual for Bridge Evaluation - Second Edition*. American Association of State Highway and Transportation Officials, 2011.
- (14) Buckland, P. G., F. P. D. Navin, J. V. Zidek, and J. P. McBryde. Proposed Vehicle Loading of Long-Span Bridges. *Journal of the Structural Division*, Vol. 106, No. 4, 1980, pp. 915-932.
- (15) Harman, D. J., A. G. Davenport, and W. S. S. Wong. Traffic loads on medium and long span bridges. *Canadian Journal of Civil Engineering*, Vol. 11, No. 3, 1984, pp. 556-573.
- (16) Flint and Neill Partnership. *Interim design standard: long span bridge loading* Contractor Report 16. Transport and Road Research Laboratory, 1986.
- (17) Ditlevsen, O., and H. O. Madsen. Stochastic Vehicle-Queue-Load Model for Large Bridges. *Journal of Engineering Mechanics*, Vol. 120, No. 9, 1994, pp. 1829-1847.
- (18) Prat, M. Traffic load models for bridge design: recent developments and research. *Progress in Structural Engineering and Materials*, Vol. 3, 2001, pp. 326-334.
- (19) Nowak, A. S., M. Lutomirska, and F. I. Sheikh Ibrahim. The development of live load for long span bridges. *Bridge Structures*, Vol. 6, No. 1, 2010, pp. 73-79.

- (20) Klein, L. A., M. K. Mills, and D. R. P. Gibson. *Traffic Detector Handbook*. FHWA-HRT-06-108. Federal Highway Administration, 2006.
- (21) Brackstone, M., and M. McDonald. Car following: a historical review. *Transportation Research Part F*, Vol. 2, 1999, pp. 181-196.
- (22) Hoogendoorn, S. P., and P. H. L. Bovy. State-of-the-art of vehicular traffic modelling. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, Vol. 215, 2001, pp. 283-303.
- (23) Orosz, G., R. E. Wilson, and G. Stépán. Traffic jams: dynamics and control. *Philosophical Transactions of the Royal Society A*, Vol. 368, 2010, pp. 4455-4479.
- (24) Hidas, P., and P. Wagner. Review of Data Collection Methods for Microscopic Traffic Simulation. Proceedings of the World Conference on Transport Research, Istanbul, 2004.
- (25) O'Brien, E. J., A. Hayrapetova, and C. Walsh. The use of micro-simulation for congested traffic load modelling of medium- and long-span bridges. *Structure and Infrastructure Engineering*, Vol. 8, No. 3, 2012, pp. 269-276.
- (26) Caprani, C. C. Calibration of a Congestion Load Model for Highway Bridges Using Traffic Microsimulation. *Structural Engineering International*, Vol. 22, No. 3, 2012, pp. 342-348.
- (27) Chen, S. R., and J. Wu. Modeling stochastic live load for long-span bridge based on microscopic traffic flow simulation. *Computers and Structures*, Vol. 89, No. 9-10, 2011, pp. 813-824.
- (28) Nagel, K., and M. Schreckenberg. A cellular automaton model for freeway traffic. *Journal de Physique I France*, Vol. 2, No. 12, 1992, pp. 2221-2229.
- (29) Treiber, M., A. Hennecke, and D. Helbing. Congested Traffic States in Empirical Observations and Microscopic Simulations. *Physical Review E*, Vol. 62, No. 2, 2000, pp. 1805-1824.
- (30) Kesting, A., and M. Treiber. Calibrating Car-Following Models by Using Trajectory Data. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2088, 2008, pp. 148-156.
- (31) Chen, C., L. Li, J. Hu, and C. Geng. Calibration of MITSIM and IDM Car-Following Model Based on NGSIM Trajectory Datasets. International Conference on Vehicular Electronics and Safety, QingDao, China, 2010, pp. 48-53.
- (32) Hoogendoorn, S. P., and R. Hoogendoorn. Calibration of microscopic traffic-flow models using multiple data sources. *Philosophical Transactions of the Royal Society A*, Vol. 368, 2010, pp. 4497-4517.
- (33) Brockfeld, E., R. D. Kühne, and P. Wagner. Calibration and validation of microscopic traffic flow models. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1876, 2004, pp. 62-70.
- (34) Punzo, V., and F. Simonelli. Analysis and Comparison of Microscopic Traffic Flow Models with Real Traffic Microscopic Data. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1934, 2005, pp. 53-63.
- (35) Kerner, B. S., and H. Rehborn. Experimental features and characteristic of traffic jams. *Physical Review E*, Vol. 53, No. 2, 1996, pp. R1297-R1300.
- (36) Cassidy, M. J., and R. L. Bertini. Some traffic features at freeway bottlenecks. *Transportation Research Part B*, Vol. 33, 1999, pp. 25-42.
- (37) Transportation Research Board. *Highway Capacity Manual - Fourth Edition*. Transportation Research Board, 2000.
- (38) Treiber, M., and A. Kesting. Validation of traffic flow models with respect to the spatiotemporal evolution of congested traffic patterns. *Transportation Research Part C*, Vol. 21, No. 1, 2012, pp. 31-41.
- (39) Schönhof, M., and D. Helbing. Empirical Features of Congested Traffic States and Their Implications for Traffic Modelling. *Transportation Science*, Vol. 41, No. 2, 2007, pp. 135-166.
- (40) Caprani, C. C., A. Lipari, and E. J. O'Brien. Load effect of multi-lane traffic simulations on long-span bridges. In: Biondini, F. & Frangopol, D. M., eds. 6th International Conference on Bridge Maintenance, Safety and Management, Stresa: Taylor and Francis, 2012.
- (41) Caprani, C. C. Bridge-to-vehicle communication for traffic load mitigation. Bridge and Concrete Research in Ireland, Dublin, 2012.

- (42) Harwood, D. W., D. J. Torbic, K. R. Richard, W. D. Glauz, and L. Elefteriadou. *Review of Truck Characteristics as Factors in Roadway Design*. Report 505. National Cooperative Highway Research Program, 2003.
- (43) Wardrop, J. G. Some Theoretical Aspects of Road Traffic Research. *Proceedings of the Institution of Civil Engineers: Engineering Divisions*, Vol. 1, No. 3, 1952, pp. 325-362.
- (44) Moses, F. *Calibration of Load Factors for LFR Bridge Evaluation*. Report 454. National Cooperative Highway Research Program, 2001.
- (45) Coles, S. *An Introduction to Statistics Modeling of Extreme Values*, Springer, London, 2001.