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MICRO-SIMULATION MODELLING OF CONGESTION DUE TO LANE CLOSURES

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Abstract

Incident clearance and road work often require the closure of one or more of the available lanes on a highway. A lane-closure causes a significant capacity reduction, which often leads to heavy congestion. Simulation of congestion events due to lane-closures is relevant both for traffic and infrastructure management. This is especially valid when trucks are involved and they concentrate on bridges or in tunnels, thus generating critical situations for loading and safety.

A better understanding of the effects of lane closures requires a realistic simulation of the merging manoeuvre of vehicles occurring in the proximity of the lane closure. Micro-simulation allows for the motion of individual vehicles and it is therefore a suitable tool for studying traffic merging.

In this paper, a micro-simulation tool made up of a car-following model and a lane-changing model is used for simulating a lane closure on a two-lane one direction stretch of road. The effects on traffic are studied, in terms of average speed, lane change rates, and truck distribution.

It is found that the lane-changing model requires an appropriate parameter calibration when applied to lane-closures. These parameters are quite different from the ones reported in literature. An alternative means of causing congestion is also tested and it is found that it can replicate the overall congestion features upstream the closure. However, there are some differences about details of the traffic features.

1. Introduction

Incident clearance and road works often require the closure of one or more of the available lanes on a highway. Data from the UK and US suggests that about one third of all the incidents implies a lane-closure [1, 2]. Besides, there may be a particular geometric road layout that has a permanent lane drop.

A lane-closure causes a significant capacity reduction, which disproportionately affects the capacity [3, 4]. When the flow demand exceeds such reduced capacity, congestion forms upstream the closure, as vehicles approaching the closure merge into the open lane.

Lane closures are strictly related to merging manoeuvres. Merging manoeuvres can be classified as mandatory lane changes, as opposed to discretionary lane changes, which take place where there are no lane closures or merging. On-ramp merging has been relatively more studied than lane closures. In fact, it is possible to select an area of study for a long time (for instance, a junction), whereas lane-closure locations are often not known, as they are a consequence of incidents or roadwork. Moreover, the merging manoeuvres are not limited to a restricted area (for instance across the on-ramp lane), but merges may occur well before the actual closure. One study [5] carried out an empirical analysis of two lane drops in the UK and US; reference [6] reproduced the macroscopic features of the UK lane drop. Another study [4] observed some lane closures on several Dutch motorways. These studies focus on the macroscopic features of traffic, such as queue discharge flow, capacity reduction and oscillations.

Since data was collected from loop detectors, no details were available about lane change activities, as well as traffic composition. A more rigorous approach would require the use of cameras for capturing the manoeuvres of the many vehicles involved in a lane change. However, this approach is still not practicable in many situations. One study [7] analysed 4 hours of traffic including 73 lane changes and classified the observed lane changes into free, forced, or cooperative. Another [8] built up a complex model for forced and cooperative merging, based on 540 observed merging manoeuvres.

Simulation of congestion events due to lane-closures is relevant both for traffic and infrastructure management. This is especially valid when trucks are involved and they concentrate on bridges or in tunnels, thus generating critical situation for loading and safety.

It is apparent that a better understanding of this phenomenon requires a realistic simulation of the merging manoeuvres of vehicles occurring in the proximity of the lane closure. Micro-simulation allows for the motion of individual vehicles and it is therefore a suitable tool for studying traffic merging.

2. Micro-simulation models

Micro-simulation models divide into car-following (single-lane) models and lane-changing (multi-lane) models. Micro-simulation has been widely used in traffic engineering and many models have been developed in the past decades, ranging in levels of complexity and accuracy [9]. Micro-simulation allows the study of the interaction between vehicles, as opposed to macro-simulation, which describes the traffic in terms of aggregate quantities such as flow and density.

Micro-simulation results should be compared to microscopic data, such as trajectory data. However, suitable microscopic data is difficult to collect and therefore microscopic models have been often calibrated and validated at the aggregated or macroscopic level [10].

Car-following models are relatively more established than lane-changing models, since suitable video data for analysing the complex lane-changing manoeuvres is modest. In fact, along with macroscopic models, some car-following models are used to describe the global effects of multi-lane traffic [11, 12]. However, these single-lane models would not be suitable for capturing the merging manoeuvres on their own.

The Intelligent Driver Model (IDM) is a car-following model, which has a modest number of physically-meaningful parameters, is collision-free, and has proven good match with real macroscopic congested traffic [11, 13]. It has also been calibrated with real trajectory data [14, 15].

In order to carry out the traffic micro-simulation, the in-house program Simba is used here. Simba implements the IDM, as well as the lane-changing MOBIL model.

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

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

where a is the maximum acceleration; v_0 , the desired speed; $v(t)$, the current speed; $s(t)$, the gap to the vehicle in front, and; $s^*(t)$, the minimum desired gap, 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 velocity difference between the current vehicle and the vehicle in front, and; b , the comfortable deceleration. The desired minimum gap s^* is limited to the minimum bumper-to-bumper distance s_0 , so that a vehicle does not overreact and does accept small gaps when the front vehicle is faster, as observed in real world [16].

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

The MOBIL lane-changing model has been proposed in [17]. The topology of a lane change event is illustrated in Figure 1 where the subscript c refers to the lane-changing vehicle, o refers to the old follower (in the current lane) and n to the new one (in the target lane). The tilde identifies the situation after the lane change. The front vehicles play a passive role, representing a "constraint" which affects the acceleration of the lane-changing vehicle. All the accelerations, current and proposed, are calculated according to the car-following model (1) and (2).

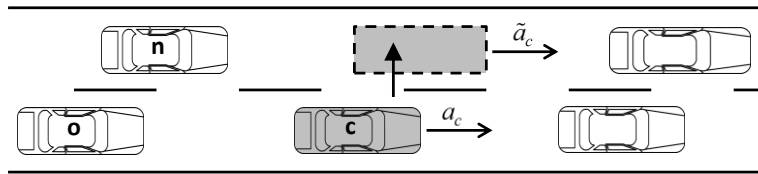


Figure 1. Vehicles involved in a lane-changing manoeuvre (adapted from [17])

A lane change occurs if both the *incentive* and the *safety criteria* are fulfilled. For a slow-to-fast lane change, the incentive criterion is expressed as follows:

$$\tilde{a}_c(t) - a_c(t) > \Delta a_{th} + \Delta a_{bias} + p(a_n(t) - \tilde{a}_n(t)) \quad (3)$$

This means that the lane-changing acceleration advantage $\tilde{a}_c - a_c$ must be greater than the sum of: the acceleration threshold Δa_{th} , which prevents overtaking with a marginal advantage; the bias acceleration Δa_{bias} , which acts as an incentive to keep the slow lane; the imposed disadvantage to new follower in the fast lane $a_n - \tilde{a}_n$, weighted through a politeness factor p . In this way, the driver aggressiveness can be adjusted with this factor. On the other hand, the incentive criterion for a fast-to-slow lane change is:

$$\tilde{a}_c(t) - a_c(t) > \Delta a_{th} - \Delta a_{bias} + p[(a_n(t) - \tilde{a}_n(t)) + (a_o(t) - \tilde{a}_o(t))] \quad (4)$$

The acceleration advantage must be greater than the sum of the acceleration threshold Δa_{th} , minus the bias acceleration Δa_{bias} (which act as incentive to move back to the slow lane), plus the disadvantage imposed to both the new follower n in the slow lane and to the current follower o in the fast lane, weighted through the politeness factor p . Equation (4) is based on [18] and it is preferred to the formulation in [17], which do not include the disadvantage to the new target follower $a_n - \tilde{a}_n$ in (4).

The *safety criterion* limits the imposed deceleration to the follower n in the target lane:

$$\tilde{a}_n(t) \geq b_{safe} \quad (5)$$

Using Equations (3) and (4), the safety criterion seldom applies, as long as the politeness factor p is not too close to zero.

The strategy of Equation (3) gives name to the MOBIL acronym (Minimizing Overall Braking Induced by Lane changes). Equations (1-5) are discretised into 250 ms steps.

3. Congested traffic states

Reference [11] has shown that congestion can be effectively generated by applying flow-conserving inhomogeneities. These consist of a local variation of the parameters, by either decreasing locally the desired speed, v_0 , or increasing the safe time headway, T . Most importantly, it has been shown that such local parameter variations act as an equivalent on-ramp bottleneck, or a lane-closure.

A bottleneck strength, ΔQ , can be defined as the difference between the outflow, Q_{out} , with the original parameter set (or without any closure) and the outflow, Q'_{out} , with the modified safe time headway T (or with the lane closure):

$$\Delta Q = Q_{out} - Q'_{out} \quad (6)$$

According to [11], the outflow Q_{out} is the *dynamic capacity*, i.e. the outflow from a congested state. It is well known that after the traffic breaks down, the outflow drops to a smaller value related to the discharge rate of the queue [19].

Depending on the inflow Q_{in} and the bottleneck strength ΔQ , the upstream traffic can take up any of the identifiable traffic states listed in Table 1. A combination of these congested states may also occur and these depend on the previous traffic history as well.

Table 1 – Definitions of various 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

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 2 and 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 desired speed, which is uniformly distributed. Trucks comprise 20% of the total flow and are randomly injected between cars in the slow lane.

Table 2 - IDM parameters

	Cars	Trucks
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

*uniformly distributed within $\pm 20\%$ (cars) and $\pm 10\%$ (trucks)

The lane-changing parameter set is based on [17], in which an on-ramp was simulated. However, when applied to lane closures, a growing queue forms on the closed lane and free traffic on the open one, which is clearly unrealistic. In fact, congestion is expected to form in both lanes with vehicles caught in the closed lane merging into the open one. Therefore, a modification of the parameters is necessary.

In proximity to the lane closure, the lane change parameter set is appropriately modified in order to allow the merging. Several tests showed that effective merging manoeuvres can be achieved by (see Table 3):

- not taking into account the neighbouring vehicles in considering the lane change execution ($p = 0$); note that in this way b_{safe} becomes the parameter which effectively controls the aggressiveness and safety of the manoeuvres;
- imposing a very high maximum allowable braking b_{safe} , equal to the maximum vehicle capability $b_{\text{max}} = 9 \text{ m/s}^2$ for all vehicles in the simulation;
- increasing the bias acceleration Δa_{bias} towards the open lane, in order to prevent vehicle from moving to the closed lane.

It must be noted that such a modified parameter set does not necessarily imply an extremely aggressive behaviour. It can also be seen as a cooperation of the follower to the front merging vehicle. In fact, such a strong deceleration rate imposed to followers generally lasts very shortly. In the real-world vehicles would "spread" their deceleration rate to let the merging vehicle cut in.

Table 3 - MOBIL parameters

	0 - 4000 m	4000 - 8000 m
Politeness factor, p	0.15	0
Changing threshold, Δa_{th}	0.1 m/s ²	0.1 m/s ²
Maximum safe deceleration, b_{safe}	9 m/s ²	9 m/s ²
Bias for the slow lane, Δa_{bias}	0.3 m/s ²	3.0 m/s ²

A two-lane same-direction 8000 m long road is considered. The lane closure is applied on the fast lane at 6000 m until the end of the road and the modified parameter set is introduced 2000 m before the lane closure. This takes into account that vehicles farther upstream may not be aware of the lane closure ahead and therefore drive normally and use both lanes.

The dynamic capacity Q_{out} of the road is 3080 veh/h. This value is computed by injecting a high inflow, which causes a cluster localised at the beginning of the road. The average outflow from such a cluster is deemed to be the dynamic capacity Q_{out} . Note that for this calculation, the MOBIL parameter set must not be modified. The reduced outflow Q'_{out} is 925 veh/h. Therefore, the capacity of the road reduces by 70%, which is close to the available real-world observations [3]. As per Equation (6), the bottleneck strength ΔQ is then 2155 veh/h.

Here we also investigate the difference between applying an actual lane closure and imposing an inhomogeneity over both lanes. The reduced outflow Q'_{out} is obtained by increasing the safe time headway to $T = 7.0 \text{ s}$. The flow-conserving inhomogeneity increases linearly from T to T' in the section 5700 - 6300 m. Note that the MOBIL parameter set (Table 3) is left unchanged in order to maintain most vehicle merging manoeuvres into the slow lane.

Four inflows Q_{in} are considered: $Q_{\text{in}} = 1500, 2000, 2500, 3000 \text{ veh/h}$. For each Q_{in} , eight simulations of one hour of traffic are run, in order to account for the randomness involved in the truck injection and vehicle desired speed.

4. Results

The capacity reduction caused by a lane closure is rather strong. According to [11], the expected congested state is the heavy HCT type. Both lanes are actually heavily congested, as a consequence of the merging manoeuvres (Figure 2).



Figure 2. Screenshot of SIMBA near the lane closure

Lane-averaged space-time speed plots are useful to visualise the spatio-temporal evolution of congestions. The plots of Figure 3 show that the congestion patterns are quite similar for a lane closure and inhomogeneity. The main difference is that some small oscillations arise when the lane closure is directly modelled (Fig. 3a), whereas these are hardly noticeable when the inhomogeneity is applied (Fig. 3b).

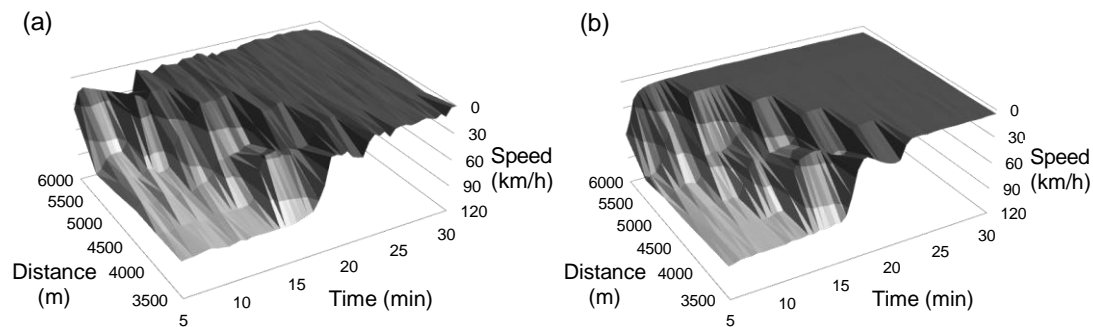


Figure 3. Space-time speed plots when applying lane closure (a) and inhomogeneity (b) ($Q_{in} = 3000$ veh/h)

A detailed analysis of the 1-minute aggregated speed at a virtual detector placed at 5000 m shows that the lane closure makes the open lane on average faster than the closed one, even though still rather slow (Figure 4a). On the other hand, when the inhomogeneity is applied, the speeds are the same in both lanes and are slightly smaller than the average of the two lanes when the lane closure is modelled. The analysis of the coefficient of variation of speed confirms the reduced oscillations when the inhomogeneity is applied (Figure 4b). These oscillations are clearly caused by the merging vehicles.

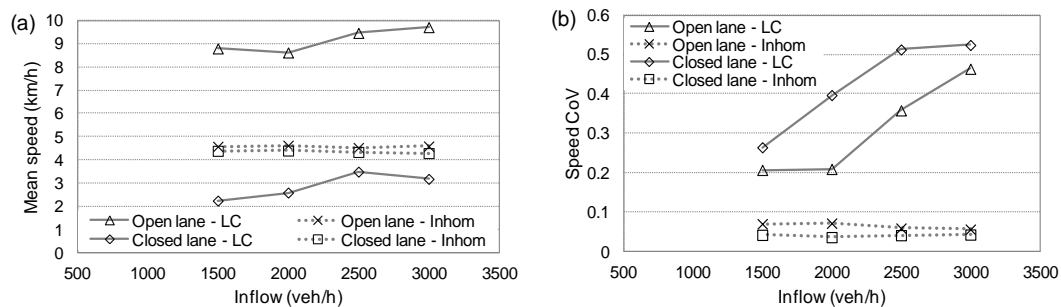


Figure 4. Average value (a) and coefficient of variation (b) of speed at 5000 m for lane closure (LC) and inhomogeneity (Inhom)

Figure 5 shows the lane change rates, separated for the space-time area in which the traffic is approaching the queue still uncongested and the area in proximity of the lane closure, where traffic is congested and merging manoeuvres take place. In the former case, it can be seen that the inhomogeneity returns a lower lane change rate for high inflows. Most importantly, such lane change rates are in the range of the available observations for two-lane motorways [20, 21]. In the latter case, the explicit modelling of the lane closures brings higher lane-change rates, which again matches the available observations [20]. As merging manoeuvres are not fully modelled with the inhomogeneity, the lane change rate is significantly lower in this case, as expected.

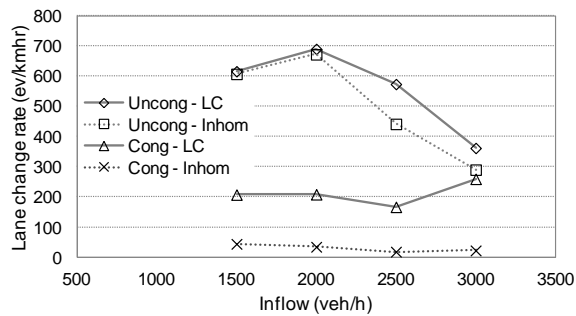


Figure 5. Lane change rates in the uncongested and congested area for lane closure (LC) and inhomogeneity (Inhom)

Finally, it is interesting to analyse the behaviour of the truck traffic. Figure 6a shows that the application of the inhomogeneity brings a higher proportion of truck traffic in the closed lane. While in the lane closure, more trucks stay in the open lane. Figure 6b shows the number of lane changes performed by trucks. This percentage is rather constant across the inflows and it is slightly higher when the inhomogeneity is applied.

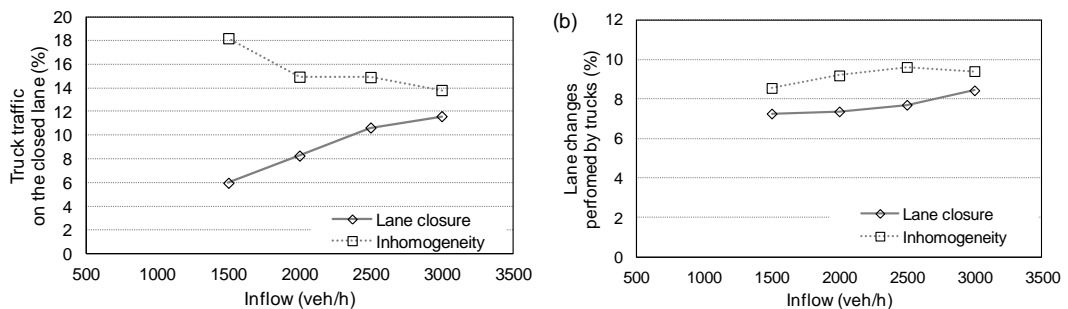


Figure 6. Truck traffic in the closed lane at the 5000-m detector (a) and number of lane changes performed by trucks (b)

5. Conclusions

This paper presents the study of a two-lane road subject to a lane closure by means of micro-simulation. Lane closures may cause heavy forms of traffic congestion. Moreover, subsequent truck concentrations may pose safety and loading issues on infrastructures.

An acknowledged car-following model, coupled with a suitable lane-changing model, is used for modelling the vehicle merging manoeuvres. Trucks are also explicitly modelled. The application of available parameter sets would not simulate any merging manoeuvre caused by a lane closure. Therefore, it is necessary to appropriately modify the lane-changing parameters in order to simulate the merging manoeuvres.

An alternative means of simulating the traffic upstream of a lane closure is also tested. It is found that such procedure can replicate the overall congestion pattern. However, when

details of the traffic are needed, such as lane change activity in proximity to the lane closure or distribution of trucks between lanes, the results can be quite different and it is better to directly simulate the lane closure.

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