EXTENSION OF A LANE-CHANGING MODEL TO A MICRO-SIMULATION TOOL

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Abstract
Traffic micro-simulation models can be divided into car-following and lane changing models. Many microscopic models have been proposed in the past. Most of them have been considered valid if capable of reproducing traffic flow conditions at aggregate level, although they should be compared to microscopic data, such as trajectory data. In spite of the progress made recently, trajectory data is still very difficult to collect, as it requires aerial photographs and intensive image processing analysis. Therefore there is still a lack of suitable data for calibration and validation of lane-changing models.

In this paper, a car-following model is combined with a lane-changing model. While in the majority of lane-changing models the lane change decision is based on a gap acceptance criterion, the model used here introduces a new approach, weighing the acceleration advantage of a current lane changing vehicle against the acceleration disadvantage imposed on the surrounding vehicles.

We show that the addition of the lane changing model to the car-following one leads to some unrealistic behaviour, which requires some adjustments in the car-following model formulation. Specifically, simulations show that overtaking vehicles cut in front of vehicles on the slow lane allowing for an inconsistent gap.

Micro-simulations are run for two-lane same-direction uncongested traffic. No on- or off-ramps are included, so the lane changes studied can be classified as discretionary, i.e. a driver changes lane because of a perceived advantage and not to follow a specific path required by the journey.

Two model modifications which lead to a more realistic behaviour are proposed. These are based on available data and do not significantly increase model complexity.

INTRODUCTION
Micro-simulation models are made up of car-following models and lane-changing models. Many micro-simulation models have been proposed in the literature and some of them include lane-changing [1].
Micro-simulation results should be compared to microscopic data, such as trajectory data. However, suitable microscopic data is very difficult to collect and therefore microscopic models have been often calibrated and validated at the aggregated level [2].

In fact, the necessary vehicle tracking for obtaining trajectory data is often a prohibitive task, which usually requires the installation of an aerial camera network and intensive image post-processing [3]. On the other hand, it is common to collect data with presence-type detectors, such as loop detectors, which are able to collect traffic data at one (or more) location. The reconstruction of the spatial traffic pattern from point detectors is often carried out through the well-known fundamental equation of traffic, which links temporal (flow) and spatial quantities (density). Doing so, it is possible to reconstruct spatial distribution of vehicles, under the assumption of each vehicle keeping its speed constant.

On the contrary, it is difficult to collect data for analysing lane-changing manoeuvres, where vehicle tracking becomes a necessary tool to capture the interaction between vehicles, which is more complex than for the car-following behaviour. Furthermore, the stretch of road has to be significantly longer in order to track full lane change manoeuvres and the duration of the campaign has to be much longer in order to collect enough lane change events.

On these grounds, suitable data for studying lane-changes is modest. Hidas [4] analysed 4 hours of traffic including 73 lane changes and classified the observed lane changes into free, forced, or cooperative. The author developed a lane-changing model for a traffic simulator.

The Federal Highway Administration promoted the NGSIM project, which made freely available video recordings of congested traffic at various sites in California [5]. The NGSIM database has been widely used for various research topics. For instance, in one of the project reports [6], 540 merging vehicles are used to build up a complex model for forced and cooperative merging. Thiemann et al. [7] studied the lane changing duration, while Aghabayk et al. [8] investigated the difference between cars and heavy vehicles during lane change manoeuvres.

Lane changes are typically classified as either mandatory or discretionary. Mandatory lane changes are performed in order to follow a specific path, while discretionary lane changes are performed because of a perceived advantage in the target lane.

Some lane-changing models involve a high number of parameters (for instance [6]), in order to describe the complex interaction between vehicles, especially when spaces are reduced. The estimation of these parameters is complicated and the computational burden may be prohibitive. These models are usually expressed in terms of gap-acceptance criterion, that is the lane change decision depends on whether the available gap is larger than a critical one.

Kesting et al. [9] proposed a lane-changing model, called MOBIL (*Minimizing Overall Braking Induced by Lane changes*). The lane change decision is expressed in terms of acceleration advantage against the acceleration disadvantage imposed on the surrounding vehicles. It has only four parameters, while it is able to realistically reproduce lane-changing patterns. It has never been calibrated with real data. MOBIL simulates the operational stage of a lane change, thus disregarding other possible route-strategic choices.

The application of a lane-change model to a car-following one may not be straightforward. In this paper, we show that the application of the MOBIL to the car-following Intelligent Driver Model (IDM) [10] requires some adjustments in the IDM itself.

**MICRO-SIMULATION MODEL**

The Intelligent Driver Model is a car-following model, which has a modest number of physically-meaningful parameters, is collision-free, and has proven good match with real congested traffic [10, 11, 12]. It has also been calibrated with trajectory data [13, 14].
In order to carry out the traffic micro-simulation, a program called \textit{EvolveTraffic} is used here. \textit{EvolveTraffic} implements the Intelligent Driver Model. The IDM simulates driver behaviour in time through an acceleration function:

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

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

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

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.

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

\textit{EvolveTraffic} has been extended to multi-lane simulation through the MOBIL lane-changing model. MOBIL can be adapted to symmetric and asymmetric passing rule. In the following, we show the asymmetric passing rule, where vehicles can use the fast lane only for overtaking, which is the standard in Europe.

As depicted in Fig. 1, 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 involved are calculated according to the car-following model (1) and (2).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{Vehicles involved in lane-changing maneouvre (taken from [9])}
\end{figure}

A lane change occurs instantaneously if the incentive criterion is fulfilled. For a slow-to-fast lane change, this expresses as follows:

\[ (t) - (t) \quad (t) - (t) \tag{3} \]

This means that the lane-changing acceleration advantage, \( - \), must be greater than the sum of: the acceleration threshold \( T_v \), which prevents overtaking with a marginal advantage; the bias acceleration \( \Delta v(t) \), which acts as an incentive to keep the slow lane; the imposed disadvantage to new follower in the fast lane \( - \), weighted through a politeness factor \( p \). Doing so, the driver aggressiveness can be adjusted with this factor.

On the other hand, the incentive criterion for a fast-to-slow lane change is:

\[ (t) - (t) \quad - \quad (t) - (t) \quad (t) - (t) \tag{4} \]

The acceleration advantage must be greater than the sum of the acceleration threshold \( T_v \), minus the bias acceleration \( \Delta v(t) \) (which act as an 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 \( p \). It is taken into account that a faster follower in the fast lane can make pressure to push a vehicle back to the slow-lane (’pushy follower’). Equation (4) is based on \cite{15}.
It must be noted that Kesting et al. [9] do not include the disadvantage to the new target follower, - in the fast-to-slow lane-changing (4). However this is included in the additional safety criterion, which limits the imposed disadvantage to the new follower:

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

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

MODEL AND SIMULATION PARAMETERS

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 1. These parameters are based on those used in [9]. A two-lane 5000 m long road is considered. The total inflow is 1425 veh/h, 20% of which are trucks. The whole inflow is injected in the slow lane and then vehicles are allowed to change lane. The flow is uncongested with a density of about 7 veh/km/lane. No on- or off-ramps are included, so the lane changes can be classified as discretionary.

Table 1 - Model parameters of IDM and MOBIL

<table>
<thead>
<tr>
<th></th>
<th>Cars</th>
<th>Trucks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired velocity, $v_0$</td>
<td>120 km/h</td>
<td>80 km/h</td>
</tr>
<tr>
<td>Safe time headway, $T$</td>
<td>1.2 s</td>
<td>1.2 s</td>
</tr>
<tr>
<td>Maximum acceleration, $a$</td>
<td>1.5 m/s²</td>
<td>1.5 m/s²</td>
</tr>
<tr>
<td>Comfortable deceleration, $b$</td>
<td>2.0 m/s²</td>
<td>2.0 m/s²</td>
</tr>
<tr>
<td>Minimum jam distance, $s_0$</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>Politeness factor, $p$</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Changing threshold, $\Delta a_{th}$</td>
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<td>0.1 m/s²</td>
</tr>
<tr>
<td>Maximum safe deceleration, $b_{safe}$</td>
<td>4 m/s²</td>
<td>4 m/s²</td>
</tr>
<tr>
<td>Bias for the slow lane, $\Delta a_{bias}$</td>
<td>0.3 m/s²</td>
<td>0.3 m/s²</td>
</tr>
</tbody>
</table>

COMBINATION OF IDM AND MOBIL

Extensive simulations have shown that the combination of the IDM and MOBIL returns an unrealistic behaviour in the fast-to-slow lane changes. Specifically, simulations have shown that overtaking vehicles cut in front of vehicles on the slow lane allowing for an inconsistent gap. This is due to the desired minimum gap, $s^*$, in (2), which may get unrealistically below zero for negative values of speed difference (when the front vehicle is faster) and consequently returns incorrect accelerations in (1), which often lead to over-reaction.

Such a situation seldom happens in single-lane simulations, where the speed difference between two consecutive vehicles is typically within a limited range, but it is common in two-lane traffic, where merging or cut-in manoeuvres can occur frequently.

Field observations showed that vehicles accept gaps shorter than usual when a vehicle that cuts in is faster [4, 5, 6]. In fact, drivers rely on the front vehicle not changing its behaviour and therefore react only mildly with little or even no deceleration. The micro-simulation models based on the above field observations allow for a gap close to the bumper-to-bumper distance when the cut-in vehicle is faster [4, 6].
Fig. 2 shows data taken from the US-101 dataset of the NGSIM project [5]. This dataset contains 45 minutes of video recording over 640 m of the US-101 6-lane freeway. The layout includes an on- and off-ramp, with an auxiliary lane in between. The video data was collected from 7:50 to 8:35 am on the 15th of June 2005. The subset from 7:50 to 8:05 am shows the highest number of lane changes, which occurs during the congestion build-up. After that, the traffic is primarily congested and the number of lane changes significantly drops, as expected.

396 lane changes are considered. 64 lane changes are discarded because involving motorcycles and 527 because either the NGSIM tracking algorithm misplaced some vehicles or a vehicle aborted a lane-changing manoeuvre. Vehicles are discarded if 1 s after changing lane, they have either not moved transversally more than 0.6 m or moved back to the initial lane.

Fig. 2a shows the observed relationship between the speed difference of the new follower and the lane-changing vehicle, and the gap between the same vehicles. It can be seen that some very close cut-in manoeuvres occur when the relative speed is less than zero (i.e. the lane-changing vehicle is faster), while the minimum gap seems to increase linearly with the speed difference when the follower is faster (the dotted lines are just indicative). Fig. 2b shows the observed relationship between the speed of the follower and the same gap as above. It can be noticed that small gaps occur also when the follower absolute vehicle speed is relatively high, confirming that the driver behaviour in lane-changing is different from the one in car-following [4].

Kesting et al. [16] acknowledged the problem of the IDM over-reaction and found an analytical formulation in the field of the *Adaptative Cruise Control* (ACC). They combined the IDM with a ‘constant-acceleration heuristic’ model (CAH). This latter model considers the acceleration of the leading vehicle and leads to a much more relaxed behaviour. The ACC differs from the IDM when the two vehicle speeds are comparable, while leads to a similar behaviour when the cut-in vehicle is slower (which represents a seriously critical situation). The ACC model requires the introduction of a new parameter. However, the combination of the ACC and MOBIL has not been tested for micro-simulation purposes and would be likely to lead to an increase in complexity and computational demand.

We therefore consider two alternative formulations to the IDM, which only modify the last term of (2) when the speed difference is negative (\( \Delta v < 0 \)). They both do not require any new parameter and do not add significant computational complexity.

Fig. 3 shows the proposed modifications. The first one simply caps (2) to the minimum bumper-to-bumper distance \( s_0 \) (*case 1*), providing a sharp discontinuity at -16 km/h. The second one provides a softer exponential interpolation (*case 2*), which has the same slope of (2) at \( \Delta v = 0 \) and asymptote \( s^* \) for \( \Delta v \to -\infty \):

\[
s^* (t) = s_0 + T v(t) \cdot \exp \left( \frac{\Delta v(t)}{2T \sqrt{ab}} \right)
\]  

(5)
MICROSCOPIC RESULTS

Fig. 4 illustrates the minimum gap allowed for a lane change, when a car cuts in the slow lane in front of a truck. If the car cuts in at its desired speed, $v_{0,\text{car}}$, it has no acceleration advantage ($a_\text{c} = 0$). If also the truck is actually going steadily at its lower desired speed, $v_{0,\text{truck}} = 80$ km/h, then $a_\text{t} = 0$ and the acceleration imposed must be according to (4):

The resulting gaps are calculated according to (2) or (5), varying the desired speed of the car, $v_{0,\text{car}}$ from 80 to 140 km/h. As expected, the IDM does not show a steady trend. After a speed of about 96 km/h, the faster the car cuts in, the bigger the gap allowed for, which is clearly unrealistic. If $v_{0,\text{car}} = 120$ km/h, as in Table 1, the car would allow for 82.5 m gap to go back to the slow lane. Modifications case 1 and 2 show a steady trend instead.

It can be seen that when the speed difference is limited, the gaps in Fig. 4 are quite large compared to the field observations and that the observed discontinuity is at about 0 km/h (Fig. 2a). This aspect is deliberately not taken into account in order to not drastically change the IDM model and because the US-101 observations may still include some ruder mandatory lane changes, where the necessity of following the planned path may force drivers to accept or impose very short gaps.

Note that using the fast-to-slow lane-changing formulation in [9], the car would cut in allowing for a smaller gap, but imposing a deceleration $\dot{b}_{\text{safe}} = 4$ m/s$^2$ to the truck. This seems too strong compared to the field observations and it may even lead to flow instability. In fact, the US-101 lane-changes analysed above show that the deceleration of the new follower was stronger than the comfortable deceleration $\dot{b} = 2$ m/s$^2$ in only 26 cases (5.5%).

Finally, it must be noted that the slow-to-fast lane changes are affected as well. However, in this case, it is the gap to the new leader to be affected, and it represents a gentler
manoeuvre than the cut-in described above. Fig. 4 can also be qualitatively regarded as the lead gap allowed for when a vehicle moves to the fast lane.

MACROSCOPIC RESULTS

Fig 5a shows the difference between the IDM and its two modifications in terms of number of lane changes during a 30 min simulation. The IDM returns almost half of the number of lane changes compared to the two modification cases. This is due to the large gap required in order to undertake a lane-changing manoeuvre (see Fig. 4). If the desired speed, $v_{0,\text{car}}$, is chosen to be 96 km/h, the number of lane changes for the IDM is roughly the same, while it would be expected to have fewer. Conversely, this does happen in the two modifications. Finally, the exponential modification leads to 10% fewer lane changes than the IDM because of the larger gaps (see Fig. 4).

![Figure 5 - Number of lane change events for $v_{0,\text{car}} = 120 \text{ km/h}$ (a) and $v_{0,\text{car}} = 96 \text{ km/h}$ (b)](image)

It is interesting to see to which extent the proposed modifications affect the simple IDM car-following behaviour, which is a more established model. Since the proposed modifications affect the driver response only when there is a speed difference between two consecutive vehicles, homogenous traffic is not suitable for testing. Therefore congestion is introduced by increasing the inflow to 2190 veh/h and increasing the safe time headway, $T$, downstream. It has been shown that such local parameter variation acts as an equivalent on-ramp bottleneck [10, 11]. The safe time headway is $T = 1.2$ s from 0 to 2700 m (see Table 1), then increases linearly to 3300 m where it reaches the value $T' = 1.8$ s. Fig. 6 plots the density in the area next to the inhomogeneity (from 2000 to 2500 m) during the 30 minute simulation.

![Figure 6 - Density in single-lane congested traffic](image)

It can be seen that the difference is negligible for case 1 and limited for the exponential decay. In this latter case, the maximum difference in a single value is 23.5%, while on average the density is under-estimated by 3%. This happens because the speed differences are limited during the single-lane simulations and, within this range, case 1 is similar to the IDM, while case 2 provides higher gaps (see Fig. 4).

CONCLUSION

We show that the use of an acknowledged car-following model returns some unrealistic behaviour when coupled to a lane-changing model. The lane-changing model is based on acceleration advantage criterion, while the accelerations are calculated according to the car-following model. In particular, this leads to an inconsistent trend in the allowed gaps during lane change manoeuvres when a vehicle cuts in faster in front of another, which is a common situation in multi-lane simulations.
Available field observations are used in order to define possible modifications. We propose two simple modifications which reflect real driver behaviour, do not significantly increase model and computational complexity, and do not twist the model conception. It is found that they both lead to similar result, providing a consistent trend in the lane-changing behaviour. It is also found that they do not significantly change the car-following behaviour in single-lane simulations.

REFERENCES