Cooperative Lane-Change and Longitudinal Behaviour Model Extension for TraffSim

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Abstract. Behaviors of drivers have an important influence on the throughput, safety and traffic flow of vehicular transportation systems. Especially in simulation scenarios, a smooth, realistic and fully reliable lane-change model is a precondition to achieve reasonable results. An extraordinary challenge is provided by situations with multiple congested lanes, including vehicles intending to change to the adjacent lane even if the target lane is occupied by vehicles stuck in a traffic jam. This paper addresses this special use case by introducing Cooperative Lane-Change and Longitudinal Behaviour Model Extension (CLLxt), which can be applied as an extension to models from literature. The result is a simple but well-functioning cooperative model, which covers both participants, the vehicle intending to change the lane and others which need to react to this intention by providing space. The utilization of CLLxt is demonstrated with an example in TraffSim.

Keywords: Lane-change model · Traffic simulation · Cooperative lane-change

1 Introduction

Behavioural models have a considerable influence on results of vehicular traffic simulation. Especially in cases where real time experiments are impossible to execute with reasonable effort, simulation of such situations are the only way to investigate different situations on the road. Numerous simulation frameworks of different types exist in literature [1–5], which make use of various models that encapsulate single tasks of the driver. The models can be separated into those which model the drivers behaviour, such as lane-change models and longitudinal models. Additionally, fuel consumption models or others which represent routing decisions can be applied. For microscopic simulations, where each vehicle is modelled as a separate entity with its special features (length and width, assigned fuel-consumption, longitudinal and lane-change models), driving tasks need to be executed fully automated on the one hand, and in a manner close to reality

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on the other hand. Single-lane car-following models have been applied in the past which successfully define vehicle movement [6]. They can describe vehicle dynamics in different situations, instabilities or congestion situations. However, simulations with real road networks and realistic results can only be executed by using multilane roads. Therefore, a well-functioning lane-change and longitudinal model are of vital importance, as they basically control the steering and acceleration of all vehicles in the simulation.

The consideration of different traffic conditions and incomplete knowledge of other vehicles intentions makes the development of a lane-change model a complex concern. Further, safety plays an important role, as well as smoothness of lane-changes and realistic behaviour. Several microscopic models can be found in literature, which all are designed for specific use cases and have their pros and cons depending on the defined requirements, the environment, density of vehicles or characteristics of the road network [7]. An essential capability of such a model is also to be applicable in different situations. The original intention of changing a lane can be (1) to change to a neighbour lane to pass by a slow vehicle, (2) to change the lane due to the traffic laws (e.g. obligation to drive on the right in Europe), (3) to leave an ending lane (highway ramp, decrease of lane number, lane closure) or (4) to follow the desired route, which would not be possible on the current lane. The latter case constitutes the main focus of this paper. In particular, turn restrictions before intersections are considered. The intention of drivers to switch to the correct lane which allows them to follow their desired route must be executed before entering the intersection in order to enable automatic route guidance through the intersection. Especially in congested situations, individual lane-changes are often not possible without the cooperation of vehicles in the neighbouring lane. A reliable performance of the model is very important in simulations. Vehicles must use the correct lane when entering the intersection and this has to be guaranteed by the model. Otherwise, unexpected and indeterministic conditions could be the consequence.

The authors introduce an extension which is applied both to lane-change and longitudinal models. The main goal is to have a versatile and safe, but very simple mechanism that avoids entries of the intersection on the wrong lane and enables following the vehicles' routes correctly. The extension is evaluated and tested by example of the lane-change model MOBIL [8], implemented in the microscopic traffic simulator TraffSim [5].

The rest of this paper is organized as follows. The next section gives an overview of existing lane-change models. The extended model MOBIL [8] is elaborated in detail. Section 3 defines requirements which are defined for the proposed model. In Sect. 4, the cooperative extension is presented. Section 5 concludes the paper and gives an overview of planned future work.

2 Related Work

The importance of microscopic traffic simulation in general and the motion of vehicles in particular is increasing continuously. Accompanied by technological progress that keeps collection of continuous traffic data getting better, simulation models for vehicular traffic receive increasing attention since the 1980s [9]. The lane change models can initially be grouped into models for driving assistance (e.g. steering wheel adjustment to perform safe lane changes) [10–12], and models for simulation purposes. These deal with the driver's decision to perform the lane change, evaluation of the surrounding environment to determine whether or not a lane change is possible and different reasons for the lane change (necessity of giving way to a merging vehicle, change for overtaking, change for leaving a closed or blocked lane).

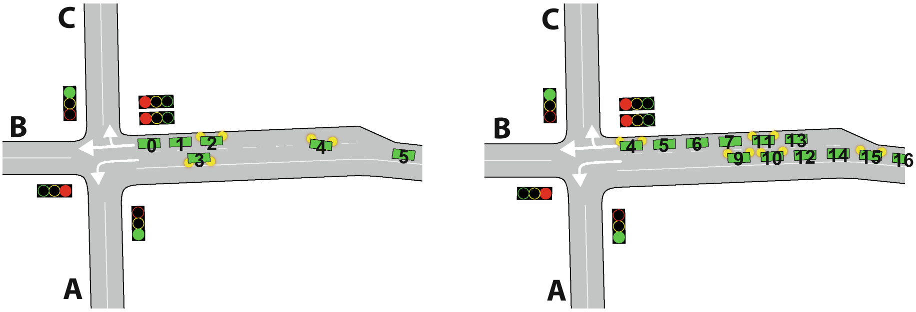
Lane-Change models for computer simulation can be classified into different categories [7]. Rule-based models, such as Gipps Model [13] or ARTEMiS Model [14]. However, those models do not consider congested situations and giving way to a merging vehicle. A different type are discrete-choice based lane-change models, like Toledo et al's Model [15] and incentive based models, such as MOBIL [8]. However, very few of the introduced models in literature consider cooperative behavior. To the authors knowledge, none of them considers special standstill situations, with multiple involved lanes and vehicles situated on the wrong lane.

The proposed extension addresses this particular question. It answers how a present combination of lane-change and longitudinal model can be extended to allow cooperative lane-changes before intersections.

3 Requirements Analysis

Basically, a lane-change model needs to consider the characteristics of the vehicles surrounding the subject vehicle, that are relative speed, positions and gaps between the potential new lead and lag vehicle. Further, it needs to function in different situations, such as congested traffic, freeflow traffic and with different speeds. An exhaustive, safe and simulation capable lane-change model needs not only to decide whether or not the current or a neighbor lane is optimal. Supplementary, it also has to deal with situations where the intended lane-change decision is impossible to execute without cooperation with other vehicles. This is essential especially in congested situations, where the target lane is occupied by other vehicles. Figure 1 shows such a situation, which is likely to happen before multi-lane intersections. In the left part, no problem will occur because the target lane for vehicle 4 is free and it can change without any problems. In contrast, Fig. 1b shows a problem situation where the vehicles 9 and 10 intend to move to the right lane that leads to exits B or C, but are blocked by vehicles 7, 11 and 13 which occupy this lane.

Vehicles 9 and 10 cannot stay on the current lane, because the upcoming intersection restricts turns to the left, which is not the intended direction. For this situation to solve, the lane-change model on its own cannot achieve satisfying results. Therefore, an interface to the longitudinal model needs to be defined, which can influence the acceleration and movement behavior to let the neighbor vehicle align and merge into the own lane. A realistic representation also requires consideration of multiple vehicles in front of the subject vehicle, on both the



(a) Free target lane (b) Occupied target lane

Fig. 1. Simple and problematic lane-change situations before intersection

right and left neighbor lanes. As soon as any of the front vehicles expresses its intent to change its lane to the subject lane, the model needs to take this into account when calculating its acceleration, speed and target lane. A deterministic strategy for providing space and letting the neighbor vehicle merge needs to be defined.

To conclude the requirements, the following aspects must be considered by a comprehensive behavioral model (including lane-change and longitudinal d movement):

1. Own interest
   (a) address lane-changes for reasons of speed advance (pass by slow vehicles)
   (b) follow own route (consider turn restrictions on lanes)
   (c) avoid standstill on obstacles or exits (accident, closed lane, road narrows)
2. Common interest
   (a) stick to traffic rules (obligation to drive on the leftmost/rightmost lane of the road)
   (b) lane-changes for providing space for other vehicles (highway-ramp)
   (c) brake for letting other vehicles change their lane

The presented model will focus particularly on the impacts of points 1.(b) and 2.(c) of the enumeration above. All other requirements are basically covered by lane-change models from literature.

4 Cooperative Lane-Change and Longitudinal Behavior Extension (CLLxt)

This section describes the extension to a given lane-change model, which then allows tactical lane-changes before intersections. It consists of two aspects which need to work together seamlessly, that are the perspective from the *invoking vehicle* **A** that needs to change its lane, and from one or more *supplying vehicle(s)* **B** providing space for vehicle **A**. The freeflow situation is not focus of this work, rather the situation before intersections as elucidated in Sect. 3. Further, route destinations are assumed to be assigned to each vehicle in the simulation. Also, basic knowledge of the road network is expected, which includes drivers awareness of turn restrictions or speed limits.

4.1 Perspective of the Invoking Vehicle

Determination of the Target Lane. First, the decision whether a lane-change is necessary to continue driving on the current route needs to be made. For performance reasons, the evaluation of the target lane is not accomplished continuously in each simulation time step, but starts not before a certain distance to the next intersection is undershot. This maximum distance d_{max} for considering lane-changes before an intersection is defined as

$$d_{max} = (t_{exit} + t_{change} * (N_{lanes} - 1)) * v_{limit}. \quad (1)$$

This equation includes the following model parameters. The time threshold in seconds before arrival of the vehicle at the intersection is defined as t_{exit}. Further, t_{change} denotes the time that is needed for a vehicle to perform a lane-change. N_{lanes} is the number of lanes on the current road segment (hence $N_{lanes} - 1$ is the maximum number of lanes to change), and v_{limit} represents the speed limit.

As soon as a vehicle's computed distance to the next intersection is lower than d_{max}, the evaluation of the preferred lane in order to follow the route starts. Figure 2 shows a multilane intersection, with necessity of changing the lane for vehicle 1, which just at the moment reaches the range of influence of CLLxt by falling below d_{max}. For a better overview, only the relevant connecting lanes are included in the intersection.

The simulator needs to determine if the current lane is appropriate for driving along the defined route. If not, as is the case for vehicle 1 in Fig. 2, the simulation framework is assumed to deliver the desired direction of change. If the change can be achieved without any issues due to occupied lanes, the activity of CLLxt ends here. Otherwise (vehicles 9 and 10 in Figure 1b), the urgency of the change is calculated and potential neighbor vehicles' speed may be influenced if necessary.

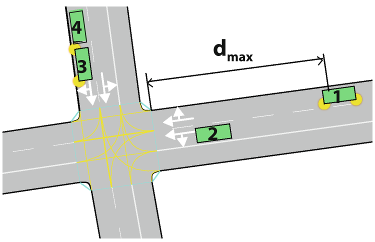


Fig. 2. Intersection with lane restrictions and required lane-change of *vehicle 1*

Urgency Function. Once a vehicle gets closer to the intersection at an inappropriate lane, the need of changing to a suitable lane becomes more and more vital. This urgency U is described by the urgency function in Eq. (2), depending on the current distance to the junction, denoted as d_{junc}. Additionally, a safety gap D is implemented, which specifies the minimal gap between vehicle and intersection border before the lane-change must be completed. Equation (3) defines the maximum needed distance d_{change} for reaching the target lane. It is also applicable for more than one lane-change by consideration of the difference in lanes between the current and target lane $n_{lanediff}$. The resulting urgency U in the interval $[0, 1]$ is used for slowing down and waiting for a chance to execute the lane-change.

$$U = \min\left[1, 1 - \frac{d_{junc} - D}{d_{change}}\right] \tag{2}$$

$$d_{change} = (t_{exit} + t_{change} * n_{lanediff}) * v_{limit} - D \tag{3}$$

Longitudinal Control. If the lane-change is not possible, the invoking vehicle needs to slow down until a safe change is feasible. In the worst case, this leads to a standstill, which can happen presumably before red traffic lights or in traffic jams.

However, the calculated urgency is used for this deceleration of the vehicle. An interface to the longitudinal model needs to be provided. We propose to simply adapt the maximum allowed speed on the current road segment, which is an input parameter for most longitudinal models [16–19] and therefore generally applicable. In TraffSim, the implemented longitudinal model IDM (Intelligent Driver Model) [19] is extended by this mechanism.

4.2 Perspective of the Supplying Vehicle(s)

In order to allow invoking vehicles to align in the lane, adaptation of the own longitudinal movement, i.e. braking may be needed to allow completion of the lane-change maneuver. Figure 3 depicts a situation, where invoking vehicles 9 and

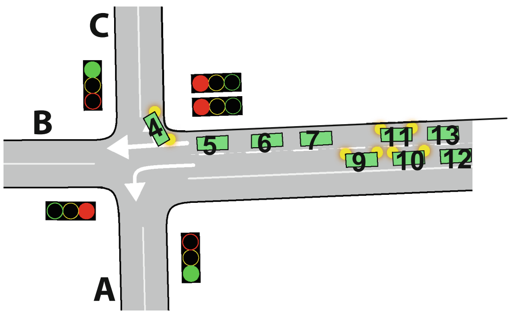


Fig. 3. Supplying vehicles *(11 and 13)* braking for invoking vehicles *(9 and 10)*

10 try to merge to the right lane to reach their destination exit C. The drivers of vehicle 11 and 13 recognize this intention through the direction indicator and reduce their speed to create a gap in front of them and let the invoking vehicles enter.

A politeness function is defined, which considers neighbor vehicles and adapts the calculated longitudinal acceleration appropriately. The following pseudocode describes the politeness function in detail, as extension to the longitudinal model. It can be parametrized by a defined amount of vehicle to look forward.

1: **function** UPDATEACCELERATION($acc_{current}, v_{current}, lookForward$)
2: $acc_{min} \leftarrow$ Infinity
3: **for** $i_{lf} = 1 : lookForward$ **do**
4: $v_{neighbor} \leftarrow$GETNEIGHBORVEHICLE($v_{current}, i_{lf}$) ▷ check for potential neighbor vehicles
5: **if** $v_{neighbor} \neq null$ **then** ▷ calculate the longitudinal gap
6: $gap_{long} \leftarrow v_{neighbor}$.position - $v_{current}$.position
7: $acc_{new} \leftarrow$ CALCACCELERATION($v_{current}, v_{neighbor}, gap_{horz}$)
8: **if** $gap_{long} > gap_{min}$ **then** ▷ check for minimal gap
9: $acc_{min} \leftarrow acc_{new}$
10: **end if**
11: **end if**
12: **end for**
13: **return** min[$acc_{current}, acc_{min}$]
14: **end function**

The method basically calculates an alternative to the standard acceleration value yielded by the applied longitudinal model. This alternative acc_{min} is determined by using the acceleration calculation function of the longitudinal model with a virtual front vehicle instead of the real front vehicle. The function GETNEIGHBORVEHICLE yields the virtual vehicle, which is the n^{th} vehicle on the right or left lane next to the current lane, where n equals the parameter $lookForward$ (line 4). Figure 4 shows examples for the virtual front vehicle determination with different $lookForward$ distances. $\{L1..L3\}$ and $\{R1..R3\}$ mark the front vehicles of vehicle V on the left and right side, respectively (as returned by the GETNEIGHBORVEHICLE function), where the index number conforms to the $lookForward$ distance. F is the direct front vehicle. After a check of the gap between the supplying vehicle and potential candidate vehicle for lane-change (line 8), which must not undershot a minimal longitudinal distance, the minimum gained acceleration (longitudinal model value or politeness value) is returned.

4.3 Application Example

The proposed model is applied within the traffic simulator TraffSim [5], as an extension of the MOBIL lane-change model [8]. The implementation supports both the IDM longitudinal model [19] and an ACC (Adaptive Cruise Control) longitudinal model [20].

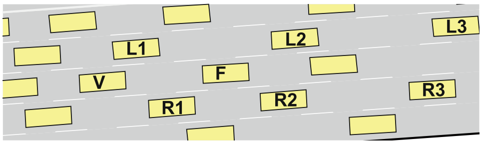
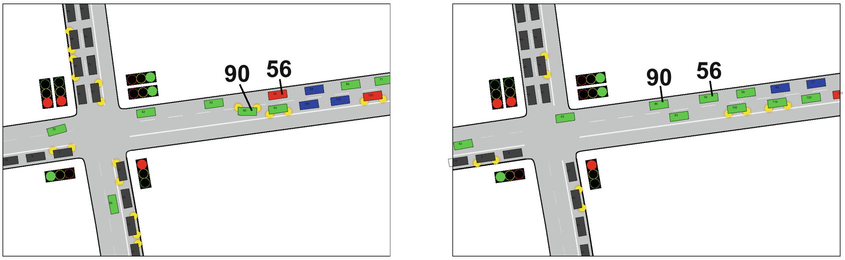


Fig. 4. Examples for neighbor vehicles with lookforward distance

Figure 5 shows the applied model in action within TraffSim, where the left part (Fig. 5a) shows the time of decision and the right part (Fig. 5b) illustrates the situation after completed lane change. The colors of the vehicles denote the current acceleration value, where green means positive acceleration, red describes negative acceleration (braking) and blue and black imply zero acceleration (steady drive and standstill, respectively).

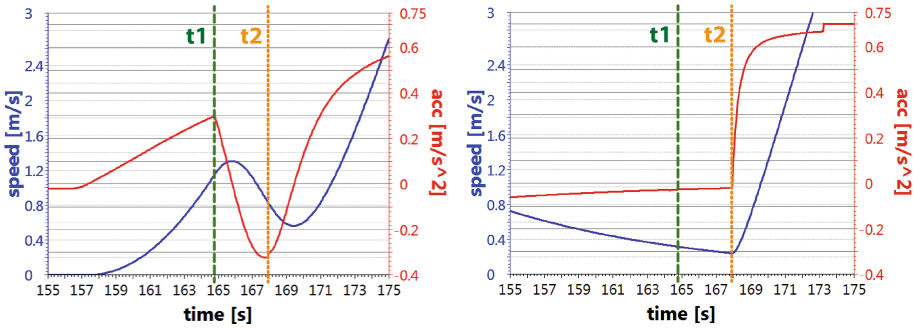


(a) Supplying vehicle 56 braking for gap creation

(b) Invoking vehicle 90 completely merged

Fig. 5. Snapshots of lane-change maneuver before intersection (Color figure online)

In order to provide better understanding of the influence of CLLxt, Fig. 6 shows history graphs of speed and acceleration over time for the affected vehicles 56 and 90, obtained from a TraffSim simulation. It's the very same situation as in Fig. 5. The blue solid line represents speed history, the red line shows the acceleration and time is plotted on the X-axis. The green dashed line *t1* and the orange dotted line *t2* mark significant timestamps. At time *t1*, the driver of the supplying vehicle (in this example number 56), recognizes the intended lane-change of the invoking vehicle (here vehicle 90). This behavior is reflected in the drop of acceleration, which becomes negative and the vehicle brakes. Thus, certainly also the speed drops and the gap between the vehicle 56 and its original front vehicle becomes larger. At time *t2*, the gap is large enough for the invoking vehicle 90 to merge. As a consequence, the acceleration and speed graphs in Fig. 6b rise and the lane-change can be completed. Figure 5a depicts the bird's view at exactly this point in time.



(a) Diagram of applying vehicle 56

(b) Diagram of invoking vehicle 90

Fig. 6. Speed and acceleration graphs for both supplying and invoking vehicles (Color figure online)

5 Conclusion and Outlook

This paper introduces an extension to existing lane-change models called Cooperative Lane-Change and Longitudinal Behavior Extension (CLLxt). It is particularly customized for application in situations where lane-change models from literature are stretched to their limits. CLLxt covers all situations which can lead to standstill of traffic flow and some vehicles are still driving on the wrong lane. This use case frequently happens before regulated multi-lane intersections, which involve multiple input lanes with turn restrictions. A change to the correct lane is then not possible due to lack of space on the target lane. CLLxt solves this by reacting to lane-change demand and creating gaps for merging. The authors present a very simple but well-functioning model for solving such situations by cooperative mechanisms. However, no bidirectional communication is assumed and thus a realistic vehicle movement is guaranteed. The utilization of the model is very simple, since it operates as extension to existing lane-change and longitudinal models. Additionally, the application of the extension is demonstrated by an example using the microscopic traffic simulator TraffSim [5], the longitudinal model IDM [19] and lane-change model MOBIL [8].

Future work will cover application of the presented model in large-scale microscopic traffic simulations. Additionally, an integration of human driver behavior into the model is planned, which covers reaction times, disturbance factors like cell phone or noise, external conditions such as rain or type of the driver (e.g. attentive, careful, aggressive).

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