An Urban Traffic Extension of a Freeway Driver Model for use in the OpenTraffic® Open Source Traffic Simulation

TRAIL Research School, October 2012

Authors

Ir. Wouter Schakel and Prof. Dr. Ir. Bart van Arem
Transport and Planning, Faculty of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands

Contents

Abstract

1 Introduction 1

2 Freeway driver model and urban modelling approach 1

2.1 Freeway driver model 1

2.2 Urban modelling approach 3

3 Driver behaviour modelling for urban situations 3

3.1 Split 3

3.2 Speed reduction 4

3.3 Yielding and having priority 4

3.3.1 Priority 7

3.3.2 No priority 8

3.4 Traffic light 10

3.5 Overview of urban driver behaviour parameters 10

4 Turbo-roundabout example 11

5 Conclusions and outlook 11

Acknowledgements 12

References 12

Abstract

This paper presents an extension of a microscopic freeway driver model for urban traffic. As urban traffic is more complex than freeway traffic, and because scientific models require extensive development, scientific models are often limited to freeways. For urban studies commercial software is often used. Models describing the behaviour in commercial software are only known to researchers into a limited extent, making them unsuitable for driver behaviour studies. Commercial software is therefore often used for studies on traffic control or safety. This paper fills some of the gap for urban driver behaviour models. Adaptations to the freeway model include an additional lane change incentive regarding intersections and an increased willingness to accelerate. New sub-models are presented for traffic lights and priority conflict. The latter includes courtesy yielding, yielding for priority traffic and keeping conflicts clear. If these models are combined with models for other modes such as public transport, cyclists and pedestrians and with realistic traffic light controllers, driver behaviour in urban traffic becomes an accessible subject for simulation research.

Keywords

Microscopic simulation, driver behaviour, intersection, conflict, traffic light

1 Introduction

Scientific research into the effects of traffic measures to improve road efficiency, emissions and safety is often focused of freeways. An important reason for this is that freeways are relatively important in terms of vehicle-kilometres on the one hand while being relatively simple to simulate on the other hand. Commercial simulation software is often used for research on urban traffic as scientific driver models for urban traffic are not readily available. The focus in scientific urban studies is often on control theory such as Lämmer and Helding (2008) and Cai et al. (2009), or on safety such as Bonsall et al. (2005) and Demir and Çavuşoğlu (2012). On freeways, driver behaviour consists of car-following, lane changing and route choice. These tasks also occur in urban traffic, though the behaviour itself is different which causes freeway models to be invalid for urban traffic. The Lane Change Model with Relaxation and Synchronization, or LMRS, (Schakel et al., 2012) has recently been developed to model freeway traffic. It is combined with a car-following model which is an adaptation to the Intelligent Driver Model, or IDM+, (Schakel et al., 2010). Currently, no route choice model is included but a fixed route is assumed. The simulation framework in which the LMRS has been developed is planned to be integrated into the OpenTraffic open source traffic simulation (Tamminga et al., 2012). The aim of this paper is to extend the freeway driver behaviour model with driver models for urban traffic.

Urban traffic has an increased complexity as drivers are faced with traffic lights and conflicts at which they either have priority or may need to yield. Lane change behaviour is also affected as drivers aim to cross an intersection as fast as possible, which makes the lane change model more complex. Willingness to accelerate is also affected. Traffic light controllers are an important part of urban traffic. Such controllers can be simple (e.g. fixed cycle) but can also become rather complex (e.g. actuated, adaptive). Finally, urban traffic includes other modes such as public transport, cyclists and pedestrians. In this paper we focus on driver behaviour regarding these aspects of urban traffic. Driver models for traffic lights and conflicts with vehicles in other streams are presented. Included in the simulation framework are fixed cycle traffic lights.

This paper is structured as follows. The next section discusses the freeway model as well as the approach to extend it for urban traffic. Section 3 elaborates on sub-models dealing with different aspects of urban driver behaviour. Section 4 gives an illustrative example of a turbo-roundabout after which section 5 presents the conclusions and outlook.

2 Freeway driver model and urban modelling approach

2.1 Freeway driver model

The freeway model consists of the LMRS lane change model and IDM+ car-following model. The car-following model is given in equation (1) where s is the net headway to a leading vehicle, v is the current speed and Δv is the approaching rate (speed difference) with the leader. Usually $\delta = 4$ is used, which is the inverse of the rate at which acceleration reduces as drivers approach the desired speed.

$$\frac{dv}{dt} = a \cdot \min\left(1 - \left(\frac{v}{v_0}\right)^{\delta}, 1 - \left(\frac{s^*}{s}\right)^2\right)$$
$$s^* = s_0 + v \cdot T + \frac{v \cdot \Delta v}{2\sqrt{a \cdot b}} \tag{1}$$

with,

a	Maximum desired acceleration
b	Maximum desired comfortable deceleration
s_0	Stopping distance
T	Desired time headway
v_0	Desired speed

The lane change model combines incentives to change lane regarding route (d_r), speed (d_s) and right-keeping (d_b) using equation (2) to derive a single desire to change from lane i to target lane j. Voluntary incentives are included with a factor θ_v as drivers ignore these if lane changes are required to follow a route. An overview of the lane change model is presented in figure 1. Total lane change desire affects driver behaviour for gap-acceptance (including relaxation) and lane change preparation (synchronization).

$$d^{ij} = d_r^{ij} + \theta_v^{ij} \cdot \left(d_s^{ij} + d_b^{ij}\right) \tag{2}$$

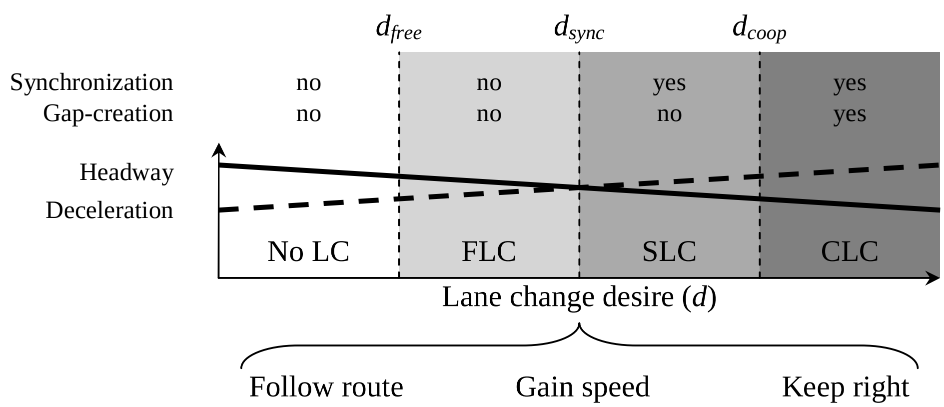

Figure 1: Overview of LMRS. Lane change desire is based on three incentives. Lane change behavior, including the accepted headway and deceleration for a lane change, varies depending on the level of lane change desire. Above the threshold d_{sync} it is assumed that drivers synchronize their speed with the target lane. For a desire above d_{coop} it is assumed that the follower in the target lane starts to create a gap as it notices the lane change desire.

In the freeway driver model, several accelerations may be determined, for instance for the leader in the current lane and for synchronization. The minimum of all relevant accelerations is applied. The simulation framework also includes road-side units (RSUs), which are defined as location based functions to which drivers may respond. RSUs are located at a specific location and drivers respond to them within x_0 = 295m by changing parameter values and/or by determining an additional acceleration value.

2.2 Urban modelling approach

The approach to include urban behavior is defined as a set of responses to different RSUs including traffic lights and conflict areas. Specific responses are discussed in the next chapter. General changes in driver behavior are discussed here.

Both traffic lights and conflict areas indicate an upcoming intersection and trigger changes in driver behaviour. It is assumed that once drivers become aware of an upcoming intersection, their acceleration behaviour changes. Drivers become more active which leads to higher accelerations. A strong indication for this is the difference in queue discharge rate of wide moving jams at freeways of about 1500 veh/h (Kerner and Rehborn, 1996) and a queue discharge rate at traffic lights of roughly 1800 veh/h. The increased accelerations are achieved by increasing the value of parameter a to a value of a_x for which 2 m/s^2 is assumed. After the intersection, the normal value for a is restored.

The lane change model is extended with an additional lane change desire regarding intersections d_x which is set as a response to both traffic lights and conflict areas (which both indicate an intersection). The total lane change desire is given in equation (3).

$$d^{ij} = d_r^{ij} + \theta_v^{ij} \cdot \left(d_s^{ij} + d_b^{ij} + d_x^{ij} \right) \tag{3}$$

The value for d_x should be a normalized value between -1 and 1 indicating the range from fully not desired to fully desired. In order to pick the best lane it is assumed that drivers consider the acceleration they can have on the current and adjacent lane. This is calculated with the car-following model which counts both a higher speed and/or a larger headway as a more positive situation. This is highly similar to the MOBIL lane change model (Kesting et al., 2007), where this is the only incentive. The acceleration difference is normalized by the maximum acceleration difference possible in regular circumstances, i.e. full acceleration in one lane and maximum comfortable deceleration in the other lane. This is expressed in equation (4). By including d_x, drivers will in principle select the shortest queue for as far as their route allows.

$$d_x^{ij} = \frac{\dot{v}^j - \dot{v}^i}{a+b} \tag{4}$$

3 Driver behaviour modelling for urban situations

This chapter elaborates on a set of responses to urban situations based on different elements of urban situations which are represented using road-side units.

3.1 Split

Within urban networks a lane may split into multiple lanes resulting in one vehicle which may have multiple downstream vehicles. Note that freeway tapers are considered a separate dead-end or starting lane in the freeway model. While being the most downstream driver on a splitting lane, drivers follow the first downstream vehicle on the lane which they will move onto. This lane is given by the route.

3.2 Speed reduction

Speed reductions are appropriate where drivers need to slow down *before* they reach a certain location. This may apply for freeways but certainly for bends at intersections. Drivers will decelerate if their speed v is larger than the required speed at the speed reduction v_r. A similar principle is applied as in the IDM (Treiber et al., 2000) where a ratio is applied on the minimum required constant deceleration b_{min}. For the ratio we have b_{min}/b where b is a parameter from the IDM+. The resulting behaviour is that drivers slowly increase the deceleration up to b if the remaining distance s allows. If the remaining distance is shorter, drivers decelerate more than required to return to comfortable levels of deceleration. The acceleration is given in equation (5).

$$\begin{aligned} \frac{dv}{dt} &= -\frac{b_{min}^2}{b} \\ b_{min} &= \frac{v^2 - v_r^2}{2 \cdot s} \end{aligned} \tag{5}$$

3.3 Yielding and having priority

Uncontrolled intersections, including roundabouts, are managed through the use of traffic rules. Traffic which crosses over a conflict area from two different directions is managed as one of the two directions has priority while traffic from the other direction may have to yield. These conflict areas (between sets of two directions) are part of the model and drivers respond to them by evaluating traffic from the own and the other direction. Note that multiple conflict areas, possibly with overlap, can be applied for interactions with multiple crossing directions. Many aspects have to be considered which leads to rather complex behaviour. Part of the behaviour is that conflicts are considered as a speed reduction, which is mostly convenient in reducing the number of RSUs required to simulate an intersection. Conflicts are also more complex because there are different types, i.e. split, merge and crossing conflicts. The length and exact location of conflicts, which are used in the conflict driver model, are determined such that the centre lines of the two lane sections considered are d_{conf} apart at the start and/or end of the conflict. Note that the start of splits is assumed to be located at the end of the splitting lane and the end of merges is at the start of the merging lane. The default value for d_{conf} is determined as half of the vehicle width and half of the lane width (½·1.75 + ½·3.5 = 2.625m) such that a vehicle stopped at the start of a conflict will never occupy any space on the conflict lane as can be seen in figure 2, where the parallel lanes describe the most critical situation for which the default value is derived. The value of d_{conf} may be adjusted for different conflicts.

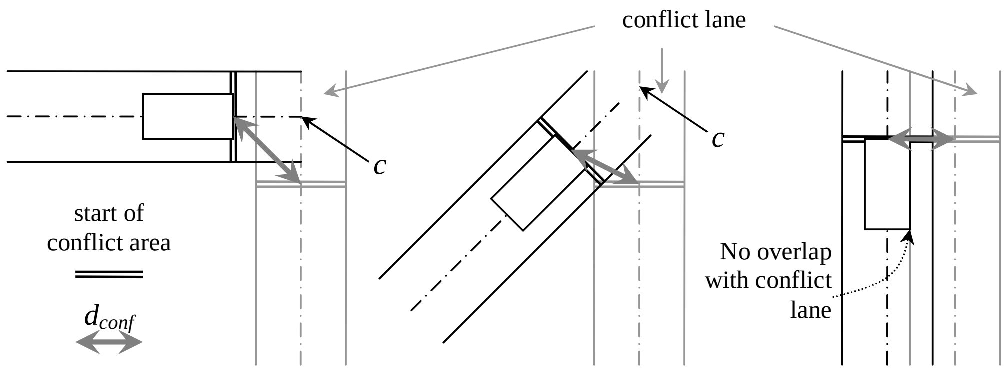

Figure 2: Influence of distance between lane centers d_{conf} on location of conflict areas for different crossing angles. Note that d_{conf} is the base of isosceles triangles where the two equal sides are on the center lines of both lanes intersecting in conflict point *c* (which is undefined for the parallel case).

Besides these common aspects there are many different responses for different types and depending on priority. These behaviours will now be discussed. The simplest conflict type are split conflicts. These are implemented to prevent that vehicles move along while the width of the lanes is not yet sufficient for two vehicles. To avoid this, the nearest downstream vehicle on the other lane which is (partially) on the conflict is followed using the car-following model. This occurs for as long as the own vehicle's front is on the conflict area.

At a merge it is also required that drivers follow each other while being in the conflict area. There is however one additional complexity which is that it is not required to follow a vehicle which is *partially* upstream of the conflict. In that case, it is sufficient to simply stop at the conflict (i.e. one can ignore the part of a vehicle which is upstream of the conflict on the conflicting lane). The car-following model is used to derive an acceleration to stop for the conflict which is considered as a virtual stand-still vehicle. The car-following model is adjusted with a stopping distance of s_c for which a value of 0.5m is assumed. This approach holds throughout this paper when 'stopping at a conflict'.

For both merge and crossing conflicts drivers either have priority or should yield. In both cases drivers need to anticipate the situation in order to determine if and how much deceleration is required, as even priority vehicles may need to stop when the conflict is being blocked or if they decide to give way as they cannot pass the conflict themselves (i.e. courtesy yielding). To anticipate the situation it is estimated how much time various vehicles with current speed v will take to cover a certain distance s assuming a constant acceleration $\tilde{a}$. Such a time estimate is given in equation (6) where $\omega < 0$ indicates that a vehicle will decelerate to a full stop before covering the distance s. Generally it is required that one event occurs before another event, e.g. clearing a conflict before another vehicle enters it. A decision to continue or to decelerate is evaluated continuously, meaning that for instance a gap which is at one moment accepted may be rejected a moment later. The continuous evaluation holds for all aspects of the conflict model, except for registering a vehicle for which a courtesy yield is performed.

$$t_{est}(s,v,\tilde{a}) = \begin{cases} 0, & s \leq 0 \\ s/v, & s > 0 \text{ and } \tilde{a} = 0 \\ \infty, & s > 0 \text{ and } \tilde{a} \neq 0 \text{ and } \omega < 0 \\ \left(\sqrt{\omega} - v\right)/\tilde{a}, & s > 0 \text{ and } \tilde{a} \neq 0 \text{ and } \omega \geq 0 \end{cases} \tag{6}$$

$$\omega = v^2 + 2 \cdot \tilde{a} \cdot s$$

The following time estimates are used in the model. The time until a vehicle will enter the conflict (*tte*), the time until the conflict is cleared (*ttc*) and the time until the conflict becomes passable (*ttp*). An overview of the distances that need to be covered regarding these time estimates is presented in figure 3. Note that *ttp* depends on the length and stopping distance of the vehicle for which the conflict needs to become passable (striped vehicle).

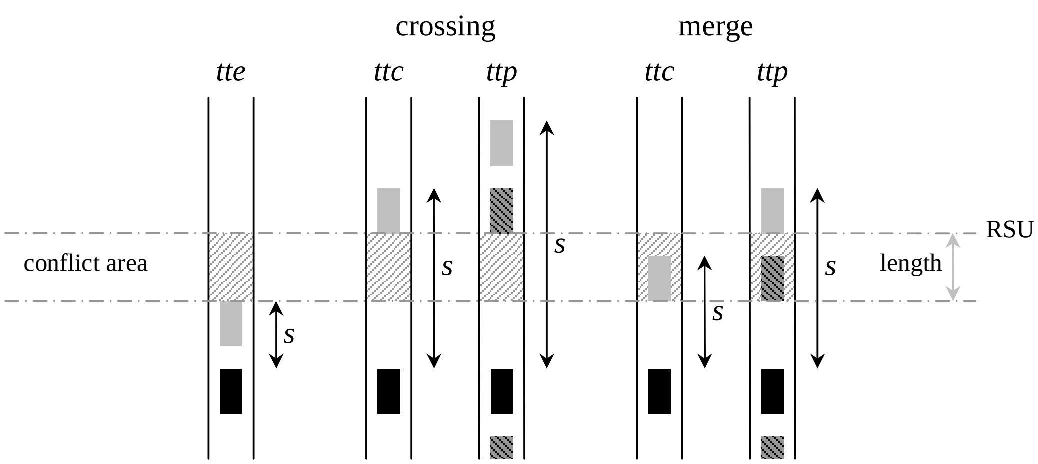

Figure 3: Distances to cover regarding time estimates in different situations. Both *ttc* and *ttp* are different between a crossing and a merge conflict as only the start of a merge conflict has to be cleared.

The time estimates can be determined for different vehicles. These are indicated with subscripts for the own vehicle (*o*), the downstream vehicle (*d*) or the conflict vehicle (*c*). For a crossing conflict the conflict vehicle is a vehicle on the conflicting lane with a separate conflict area which is (partially) upstream of the end of that conflict area. For a merge conflict it is the first vehicle fully upstream of the start of that conflict area. Finally, the times can be estimated assuming various acceleration values. These are indicated with superscripts for zero acceleration or constant speed (*z*), maximum comfortable deceleration (*b*), actual current acceleration (*a*) and finally the current free acceleration (*f*). The current free acceleration can only be used for the own vehicle and is given by the free flow term of the car-following model. This is given in equation (7).

$$\tilde{a} = \dot{v}^f = a\left(1 - \left(\frac{v}{v_0}\right)^{\delta}\right) \tag{7}$$

The behaviour for having priority or not which is based on the time estimates is explained in the next two sections.

3.3.1 Priority

The simplest model for drivers with priority would be that they ignore the conflict. However, the conflict may be blocked by crossing traffic or the driver itself may decide to yield out of courtesy. The latter often occurs if drivers are unable to pass the conflict themselves anyway. It is assumed that a driver yields out of courtesy if all the following criteria are met:

1. The driver shows courtesy yielding behaviour. For this a certain fraction of drivers χ can be assumed, which is a parameter of the model.
2. The conflict vehicle (without priority) is not tagged as being blocked due to its own downstream conditions for any conflict (this is explained further on).
3. The vehicle is the first upstream vehicle of the conflict (i.e. there are no vehicles between the own vehicle and the conflict).
4. The downstream vehicle is not the vehicle that was registered as being yielded for at the specific conflict. This may occur at a merge where the conflict vehicle becomes the downstream vehicle. In that case the other vehicle should be followed instead of stopping for the conflict. This also means that only one vehicle will be yielded for at a merge. At a crossing, this can be a larger number.
5. The conflict is on the route of the conflict vehicle.
6. Either of the following:
    a. The conflict vehicle was registered at an earlier time as being yielded for at the conflict. This ensures that a yield decision does not alternate.
    b. $tte_o^z < ttp_d^z$ and the speed of the conflict vehicle is zero. The inequality is a method to detect congestion as the conflict becomes passable after it is entered.

A driver which decides to yield will stop at the conflict, but only if this can be performed with acceleration above –b. Otherwise no acceleration to stop is applied. The vehicle that is yielded for is registered as being yielded for at the given conflict. This, in combination with criteria 6a, makes the yield a decision instead of a continuous evaluation. Still, the yield is unregistered if the speeds of both vehicles are zero (or if the conflict is entered). The former end criterion assures that two vehicles do not get stuck in a deadlock and that the yielding vehicle will not stop for an unreasonable long time.

If a driver with priority does not decide to yield, it may need to avoid a collision with a conflict vehicle which is (partially) at a crossing conflict. Note that collisions are automatically prevented at a merge as vehicles on the merge are followed. Whether a collision needs to be avoided at a crossing conflict is determined with $tte_o^f < ttc_c^z$, i.e. the vehicle will enter the conflict before the conflict vehicle will clear it. If a collision needs to be avoided, it can be seen that the conflict may not be entered during a time of ttc_c^z. The required acceleration is given in equation (8) which is derived from constant acceleration and where x_c is the distance to the conflict start. Note that this is different than stopping at a conflict as the vehicle may only need to slow down.

$$\dot{v} = \frac{2 \cdot \left(x_c - s_c - v \cdot ttc_c^z \right)}{\left(ttc_c^z \right)^2} \tag{8}$$

The acceleration from equation (8) may project that a vehicle slows down to a full stop and then starts to move backwards such that the nose of the vehicle is at the start of the conflict after ttc_c^z. With equation (9) this can be checked as it will take less time to reach a speed of zero. In that case, the driver will stop at the conflict instead of applying the acceleration of equation (8).

$$\frac{v}{\dot{v}} < ttc_c^z \tag{9}$$

A second condition to avoid a collision at a crossing is that the conflict vehicle should have a non-zero speed. This means that a vehicle with priority may virtually go through a stand-still conflict vehicle on the crossing. However, without this rule a deadlock may arise where a few streams are blocking each other. In reality drivers may manoeuvre into small gaps, backwards, or even onto curbs, effectively preventing such situations.

A last part of the priority model is that a driver will tag itself as being blocked if it has to avoid a collision, its speed is zero and either $ttc_c^z = \infty$ or $ttp_d^z = \infty$, which means that it will not be able to pass the conflict unless either the conflict or downstream vehicle respectively starts moving.

3.3.2 No priority

Drivers without priority evaluate the current gap with the conflict vehicle and either decide to stop or to go. The class of models that is used for this is often referred to as gap-acceptance models. Often these models use a fixed gap threshold as required from the start of crossing the conflict or after having crossed the conflict. We use a relative uncertainty factor $\lambda > 1$ instead, which is used to increase a time estimate that should be smaller than some other time estimate. In this paper we use $\lambda = 1.25$. For a crossing conflict the following ordered rules apply:

1. The gap is rejected if the vehicle is upstream of the range where the priority road is visible x_{view}. This range is a property of the conflict which depends on visual obstructions from for example trees and buildings.
2. The gap is accepted if the conflict vehicle will not pass the conflict due to its route. This assumes perfect indicator use, but also avoids unrealistic situations where one vehicle is a conflict vehicle regarding multiple conflicts of another vehicle.
3. The gap is accepted if the following criteria are met:
    a. $ttp_d^z \cdot \lambda < tte_c^a$, i.e. the downstream vehicle is expected to allow sufficient space to pass the conflict when the conflict vehicle is expected to enter the conflict at its current acceleration. This only holds for crossing conflicts which need to be kept clear, which is a property of the conflict and depends on the location of the conflict on the intersection.
    b. $ttc_o^f \cdot \lambda < tte_c^a$, i.e. the conflict is expected to be cleared before the conflict vehicle is expected to enter the conflict at its current acceleration.
    c. $ttp_d^b \cdot \lambda < tte_c^b$, i.e. the conflict vehicle can decelerate comfortably and still enter the conflict after the conflict will be cleared, even if the downstream vehicle will decelerate comfortably. This is a ‘comfortable worst case’ safety criterion. This is illustrated in figure 4a.

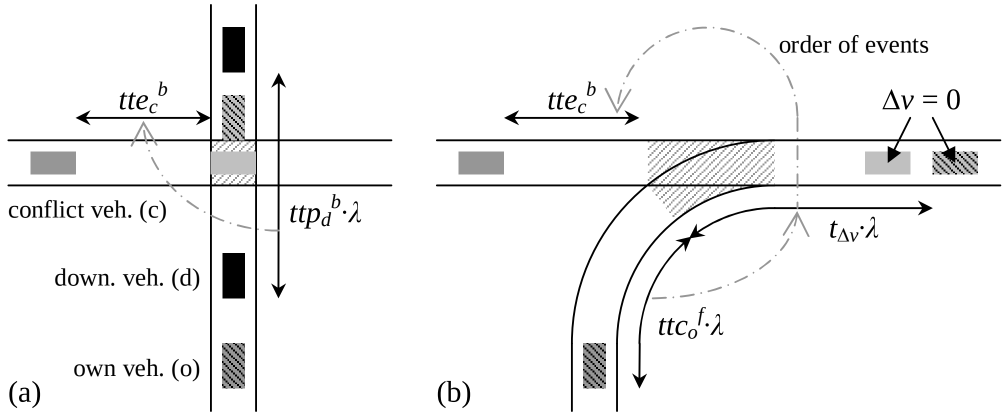

Figure 4: Safety criterion for gap-acceptance at a crossing conflict (a) and a merging conflict (b).

For a merging conflict the conditions to accept a gap are slightly different. First of all, the condition 3a for crossing conflicts is not valid as this concerns letting through traffic into another direction. Also the two vehicles may become each others follower or leader after the conflict. Therefore, speed differences after the conflict need to be considered. The condition 3c for crossing conflicts is therefore adapted to $(t_{\Delta v}+ttc_o^f)\cdot\lambda < tte_c^b$, where $t_{\Delta v}$ is additional required time to overcome a speed difference. This is visualized in figure 4b. The time at which the speed difference is considered is ttc_o^f. It is expected that the own vehicle will accelerate with the free acceleration while the conflict vehicle decelerates with b. This results in a speed difference which (if positive) needs to be overcome with an extended deceleration of the conflict vehicle of b. This leads to equation (10) for the additional time required at a merge for the third condition.

$$t_{\Delta v} = \max\left(\frac{v_c - b \cdot ttc_o^f - v_o - \dot{v}_o^f \cdot ttc_o^f}{b}, 0\right) \tag{10}$$

Both for crossing and merging conflicts, a non-priority vehicle will stop in front of the conflict if the gap is rejected. Additionally, if a gap of one conflict is rejected it may be required to stop for another conflict further upstream. This happens if conflicts are close together and need to be kept clear. Once a driver decides not to accept the gap at a conflict, it evaluates whether the next upstream conflict that needs to be kept clear, but the start of which is also downstream of the vehicle, allows sufficient space after it. The space between the conflicts needs to be at least the vehicle length plus s_c. If the space is insufficient, the decision is made to stop for the upstream conflict. The same principle is applied again which may lead to a series of conflicts which are all kept clear because there is never sufficient space in between and the gap of the last conflict is rejected. More concrete, this constitutes crossing the intersection, at least up to a buffer area, at once. If a driver will stop in front of a conflict, the simulation may ignore conflicts further downstream for efficiency, as these can never lower the acceleration.

Finally, if a gap at a crossing is rejected, a non-priority driver may tag itself as being blocked if its speed is zero and either $ttp_d^z = \infty$ or $ttc_c^z = \infty$, i.e. the conflict can only be passed as soon as the downstream or conflict vehicle respectively starts moving.

3.4 Traffic light

To a driver a traffic light is an object which is in any of three states. For the driver model we consider only two states: red/yellow or green. In case the traffic light is green, it is ignored. If the traffic light is either red or yellow, drivers will stop in front of it if the required deceleration is within limits. Note that the yellow time should be designed such that drivers may only consider the deceleration as to strong if they can pass the traffic light during the yellow phase. The acceleration regarding the traffic light is calculated using the car-following model where the traffic light is regarded as a stand-still vehicle. There are two slight adjustments to the car-following model. First, the regular value of maximum comfortable deceleration b is not applicable at traffic lights. Instead, a value of b_{yellow} is used for which we assume a value of 3.5 m/s^2 (taken from FOSIM, Dijker and Knoppers, 2004). This value complies with design guidelines of traffic lights and is usually larger than b. Second, if the resulting acceleration results in a deceleration stronger than b_{yellow}, the acceleration is not applicable and the traffic light is passed during the yellow phase (usually).

3.5 Overview of urban driver behaviour parameters

The preceding sections have covered various aspects of driver behaviour regarding urban traffic. This behaviour is explained in models which use a set of five parameters, see table 1. The most important parameter is a_x which is the acceleration at traffic lights and conflicts. Consequently it largely determines capacity of both controlled and uncontrolled intersections, including roundabouts. The maximum accepted deceleration at traffic lights is given by b_{yellow}, which is strongly correlated to the duration of the yellow phase and thus possibly jumping a red light.

Table 1: Overview of urban driver behavior parameters

Symbol	*Value*	*Meaning*
a_x	2 m/s^2	Maximum acceleration at intersections
b_{yellow}	3.5 m/s^2	Maximum deceleration at traffic lights
s_c	0.5 m	Stopping distance at conflict areas
λ	1.25	Safety factor on estimated times at conflict areas
χ	1	Fraction of drivers which shows courtesy yielding behaviour

Other parameters are related to conflicts. There is a stopping distance s_c which is mostly in place to prevent numerical overshoot of the start of conflict areas. The value should be small as larger values will increase the distance that non-priority vehicles have to cover during acceleration before clearing a conflict, which decreases capacity. More significant for the capacity is λ which is a safety factor to be sure that one event occurs before another, e.g. clearing the conflict before the conflict vehicle enters the conflict. Different values between drivers could be used to reflect that some drivers are more cautious than others. Values close to one should however be avoided, as some safety buffer is required due to inexact time estimates for the gap-acceptance. Finally we have χ which is the fraction of drivers that show courtesy yielding behaviour when they have priority but cannot clear the conflict.

Note that d_{conf} and x_{view} are also of influence at conflict areas. These are not considered as parameters as they are correlated with geometry, i.e. they are part of the network.

4 Turbo-roundabout example

As an illustration and face validity test of conflict driver behaviour we perform a simulation of a four leg turbo-roundabout as in figure 5. Each of the four incoming links has a demand of 1500 veh/h, which fully saturates the roundabout. Turn fractions are such that north- and south-bound traffic is twice that of east- and west-bound traffic. Figure 5 shows several aspects of the implemented models.

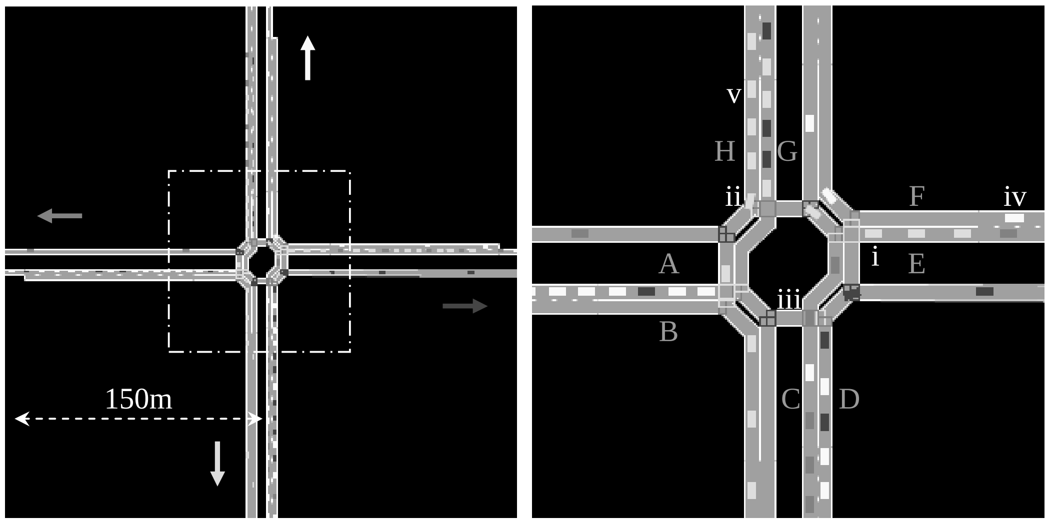

Figure 5: Vehicles at a turbo-roundabout with i) driver stopping in front of the first of two conflicts as the gap at the second is not accepted and the first needs to be kept clear, ii) driver accepting a merge conflict with nearby conflicting traffic, iii) driver accepting a crossing conflict without nearby traffic, iv) north-bound driver having changed right due to intersection incentive despite having to change left within about 200m and v) south-bound traffic dividing over both available lanes depending on presence of other traffic.

The resulting flows are in the order of 250–400 veh/h on the lanes without priority (A, B, E & F) and in the order of 500–700 veh/h on the lanes with priority (C, D, G & H) giving a total flow over the roundabout of about 3750 veh/h. These values are reasonable as the model is not calibrated. Differences between B and F (or A and E) are insignificant indicating that the intersection lane change incentive overrules the route incentive despite a required lane change in about 200m after location F. Note that the route incentive would be larger if the right north-bound lane would end less than 150m after the roundabout.

5 Conclusions and outlook

In this paper an extension for urban traffic of the LMRS lane change model combined with the IDM+ car-following model for freeways is presented. Driver behaviour is adapted using an additional lane change incentive regarding intersections and by changing the acceleration parameter representing more willingness to accelerate. Additional models have been developed for speed reductions, traffic lights and conflict areas. Behaviour at conflict areas includes courtesy yielding, regular yielding and keeping conflicts clear.

The focus in this paper is on driver behaviour. For a complete urban simulation more is required. From the infrastructure side this involves public transport lanes/tracks, bus stops, pedestrian/cyclist crossings etc. The other modes also require their own behavioural models. Connected to the infrastructure are controllers, of which traffic light controllers are the most frequent and important. These extensions to the simulation framework should be developed for urban implementation.

Finally, the presented models have not been calibrated. Although the assumed values appear to result in reasonable flows at a turbo-roundabout, calibration with real data should be performed. The urban models use a total of five parameters which limits the effort required for calibration.

Acknowledgements

The research reported in this paper was conducted as part of the Connected Cruise Control project funded by the Dutch Ministry of Economic Affairs under the High Tech Automotive Systems program, by the universities of Delft, Twente and Eindhoven and NXP, NAVTEQ, TNO, Clifford, Technolution, Rijkswaterstaat and SWOV.

References

Bonsall, P., R. Liu, and W. Young (2005) Modelling safety-related driving behaviour - Impact of parameter values, in: *Transportation Research Part A: Policy and Practice*, Vol. 39, issue 5, pp. 425 - 444.

Cai, C., C.K. Wong, and B.G. Heydecker (2009) Adaptive traffic signal control using approximate dynamic programming, in: *Transportation Research Part C: Emerging Technologies*, Vol. 17, issue 5, pp. 456 - 474.

Demir, M., and A. Çavuşoğlu (2012) A new driver behavior model to create realistic urban traffic environment, in: *Transportation Research Part F: Traffic Psychology and Behaviour*, Vol. 15, issue 3, pp. 289 - 296.

Dijker, T., P. Knoppers (2004) FOSIM 5.0 Gebruikershandleiding, FOSIM 5.0 User manual, www.fosim.nl.

Kesting A., M. Treiber, and D. Helbing (2007) General Lane changing Model MOBIL for Car-Following Models, in: *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1999, pp. 86 - 94.

Kerner B. S., and H. Rehborn (1996) Experimental features and characteristics of traffic jams, in: *Physical Review E*, Vol. 53, no. 2, pp. R1297 - R1300.

Lämmer, S., and D. Helbing (2008) Self-control of traffic lights and vehicle flows in urban road networks, in: *Journal of Statistical Mechanics: Theory and Experiment*, Vol. 2008, issue 5, art. no. P04019.

Schakel, W.J., V.L. Knoop and B. van Arem (2012) LMRS: An Integrated Lane Change Model with Relaxation and Synchronization, in: *Proceedings of the 91st Annual Meeting of the Transportation Research Board*, 22-26 January 2012, Washington D.C. (to appear in Transportation Research Records: Journal of the Transportation Research Board).

Schakel, W.J., B. van Arem, and B. Netten (2010) Effects of Cooperative Adaptive Cruise Control on Traffic Flow Stability, in: *Proceedings of the 13th International IEEE Conference on Intelligent Transportation Systems* (ITSC 2010), pp. 759 - 764.

Tamminga, G., M. Miska, H. van Lint, E. Santos, A. Nakasone, H. Prendinger, and S. Hoogendoorn (2012) Design of an Open Source Traffic and Travel Simulation Framework, in: *Proceedings of the 91st Annual Meeting of the Transportation Research Board*, 22-26 January 2012, Washington D.C.

Treiber, M., A. Hennecke, and D. Helbing (2000) Congested traffic states in empirical observations and microscopic simulations, in: *Physical Review E. 62*, pp. 1805 - 1824.