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Simulation of Urban Traffic Control: A Queue Model Approach

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Abstract

This paper aims at an agent-based simulation of the interplay between two types of agents within a transport system: travelers, and traffic signals. For the simulation of this interplay, a computationally efficient traffic model is needed. It is thus shown how queue models can be used to model traffic flow and spill-back at signalized intersections.

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1. Introduction

The interplay between heterogeneous travelers and traffic signals in a transport system can be modelled by an agent-based approach [1]. When traffic signal control is traffic-actuated or adaptive and no strict mathematical formulation exists, an agent-based approach is useful to model the interaction between signal control on the one hand, and travelers' choice of departure times and routes on the other hand. In such a setup, one has to cope with the problem that traffic signals react to traffic flows while travelers react to improved traffic signal performance [2]. In the present paper, a traffic-actuated control is used that can be seen as "simple reflex agent" [3], i.e. sensors monitor the environment, and by condition-action rules the traffic signal control determines what to do next. Such a traffic-actuated control is used in practice, and it is a simple extension to fixed-time control. Travelers, in contrast, are modelled as utility-based learning agents that act in a partially observable, stochastic, sequential, dynamic, continuous and multiagent context [3]. Even if the precise specification of traveler and traffic signal agents is kept simple, complexity results from the interaction between the agents. In order to simulate mutual reactions, one needs a computationally fast traffic flow model that treats vehicles as atomic units and captures all relevant properties of traffic signal control and traffic flow.

Popular models for the simulation of traffic flow on roads are, e.g., the "cell transmission model" [4, 5], "car following models" [6, 7] or the "Nagel-Schreckenberg model" [8]. Despite all differences, the models share a common attribute: they are computationally relatively expensive. Therefore, in the domain of transport engineering, queue models have been developed [9, 10, 11, 12].

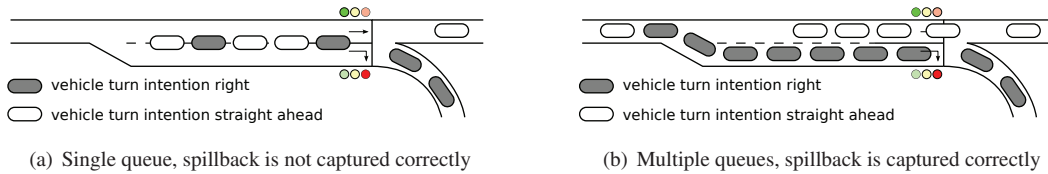


Fig. 1. Influence of traffic signals on traffic flow and spill-back can only be modelled by a queue model if it considers lanes.

Queue models disregard most of the details of vehicle movements on a road. Traffic networks are modelled as graphs. Each vertex models a crossing. Vertices are connected by *links*, a directed edge that describes a road segment. Each link of a road network is described by the following attributes: maximum flow (capacity) c_{flow} , length l , and the amount of vehicles that fit on the link $c_{storage}$ if cars stand bumper to bumper. As vehicles cannot be divided into parts (number of vehicles $\in \mathbb{N}$) one has to consider the case where $c_{flow} \notin \mathbb{N}$, i.e. $c_{flow} = \text{floor}(c_{flow}) + \text{frac}(c_{flow})$ ¹.

In the next section several existing queue model approaches are reviewed. Then, sec. 3 shows how these models can be combined and refined in order to model signalized intersections. Some illustrative simulation results using the developed model are reported in the subsequent chapter. The paper ends with a conclusion.

2. Related Work

“Fast Lane” model by Gawron. Gawron’s “Fast Lane” is a queue model that is explicitly designed for high speed mesoscopic traffic simulation [13, 9]. Vehicles entering a link have to stay on that link at least as long as they would travel at their desired velocity v_0 . During this time no computation needs to be done, the vehicles are stored in a priority queue. Afterwards the vehicle is placed into one of several point queues, one for each downstream link. These point queues jointly restrict the outflow of the link; the documentation remains unclear as to how the joint link capacity is shared between the point queues. In each simulated timestep $\text{floor}(c_{flow})$ vehicles may leave the point queue plus one additional vehicle if a random number r is smaller than $\text{frac}(c_{flow})$. If there is space available on the downstream link, i.e. the number of vehicles is less than $c_{storage}$, a vehicle is moved to the downstream link. This makes the model capable to model spill-back. Gawron states that the nodes of the model can, in principle, model signalized intersections. However, there are no further specifications. Approaches of an intersection are processed in a fixed sequence. Thus, if spill-back occurs, some links are served with a higher priority than others. Therefore the model was extended by a probabilistic prioritization of approaches to an intersection [10, 11].

Mesoscopic traffic signal simulation model by Cremer and Landefeld. Cremer and Landefeld [12] propose a mesoscopic traffic model focussing on the modelling of signalized intersections. The principles of the model for the movement on a single link are quite similar to the model of Gawron. Relevant differences are a simple specification for vehicle movements on all parts of the link, and a logic to capture unprotected left-turns. Furthermore the maximum flow of links is set up via the sampling time of the model, i.e. simulated flow rates at signalized intersections have plausible values only if a uniform velocity of $50 \frac{\text{km}}{\text{h}}$ and a sampling time of 2sec are used. The calibration of the model via the sampling time implies that flow rates are equal for all links. Waiting queues for distinct turning movements, including their spatial extension are modelled explicitly. Thus, in case of spill-back mutual blocking effects between several turning directions are captured. This is important if traffic signals are simulated microscopically as can be seen in Fig. 1: If a single queue is used (Fig. 1(a)), the first vehicle blocks all other vehicles upstream. This models reality correctly if the approach has only one lane for all turning moves. In the case, however, that the approach has several lanes for signalized turning-moves, a single queue model distorts the effects of signalization. In contrast, Fig. 1(b) shows the modelling approach from [12]. Vehicles with distinct turn intentions do not block each other until the available space for queuing on the lane is used completely.

¹ $\text{floor}(x) := \lfloor x \rfloor$, $\text{frac}(x) := x - \lfloor x \rfloor$, $x \in \mathbb{R}^+$

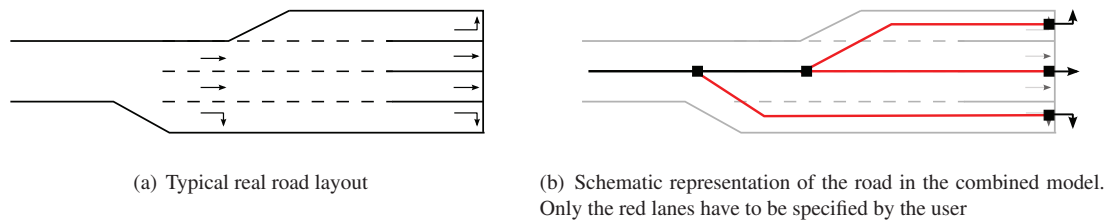


Fig. 2. Transition from real road segment to link with lanes of the combined model

Extension of Gawron's "Fast Lane" model. The traffic flow simulation of the MATSim framework (www.matsim.org) is based on Gawron's model. However, the implemented model was modified at some points: *First*, in order to calculate the minimum time a vehicle has to stay on a link the MATSim model uses a speed limit attribute of a link instead the desired velocity of vehicles. This change was undertaken due to some artefacts of the model in case of spill back: In "Fast Lane" vehicles with a high desired velocity can overtake vehicles that have a low desired velocity even in situations where the link is completely jammed. *Second*, instead of using a point queue for each turning move, the MATSim model uses only one queue for all turning moves. *Third and last*, the random draw to model the fractional part of c_{flow} in "Fast lane" is replaced by a deterministic version that accumulates fractional capacity per time step until this is sufficient for a full vehicle. This change was done in order to improve the simulation of small samples of demand: For prototyping or sketch planning usually 1 % or 10 % samples of the transport demand are used in order to save computation time. A 1% sample, together with a flow capacity of, say, $900veh/h = 0.25veh/sec$, leads to a simulated flow capacity of $0.01 \times 0.25veh/sec = 0.0025veh/sec$. An random draw based on such a small probability leads to very large fluctuations, making link travel times very unpredictable for vehicles.

3. Queue Model for traffic signal simulation

The reviewed queue models are designed to simulate network wide traffic efficiently. However, all show some drawbacks. In this section, the advantages of the models are combined to a model that no longer possesses most of the disadvantages.

Drawbacks of existing models. The Cremer and Landefeld model has two drawbacks. First, the modelling of vehicle behavior on all parts of the link needs additional computation time. However, gains in expressiveness of this part of the model are limited, as the main use cases are visualization and to provide meaningful sensor information. This information can still be calculated if needed. Second, the flow restrictions of the links are determined via the sampling time of the simulator and are homogeneous for all links. The assumption of homogenous flow at all intersections makes it difficult of not impossible to calibrate large-scale scenarios. Furthermore, most traffic signal control strategies update each second and not every 2 seconds.

The model proposed by Gawron and its extension ignore that at signalized intersections queues divide into multiple lanes that block mutually if one of the lanes is completely jammed.

The combined model. The drawbacks of the existing models can be eliminated. The traffic flow dynamics is taken from the extended Gawron model while the modelling of lanes and spill-back is taken from the Cremer and Landefeld approach. Fig. 2(a) depicts a link of a traffic network with several turning lanes at its end. The Layout of the corresponding link in the combined model is shown in Fig. 2(b). The link is partitioned into several segments (lanes). Traffic on each lane is simulated like traffic on a link in the extended version of the Gawron model. If a lane represents several lanes in reality, $c_{storage}$ and c_{flow} can be increased accordingly. At the beginning of the link only one lane may exist. Vehicles enter this lane and obtain an earliest exit time according to length and speed. Afterwards, in each timestep c_{flow} vehicles may leave the lane. The next lane is determined by necessity to be in the correct turning lane for the next downstream link

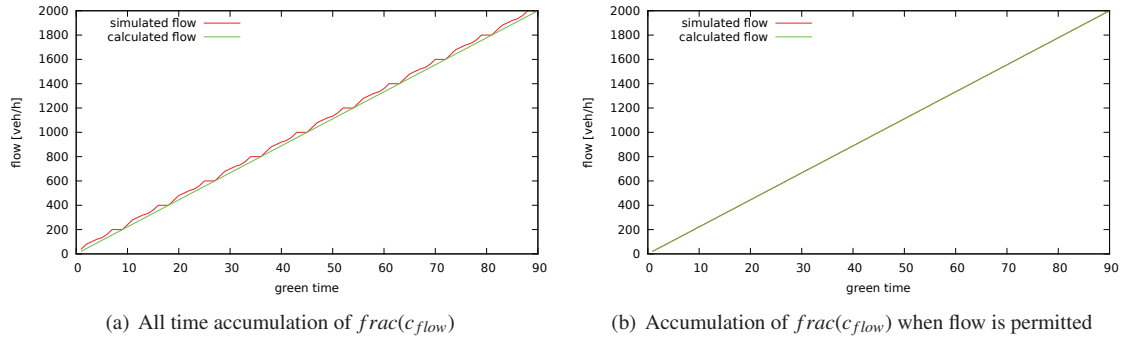


Fig. 3. Theoretic calculation vs simulation results

of the vehicle's precomputed route. If that lane has some space, the vehicle is placed on it. According to the Cremer and Landefeld approach, the vehicle is placed on the lane that currently contains the smallest number of other vehicles if there are several lanes leading to the same downstream link. Note that the lanes of the model have no 1:1 relation to the lanes existing on a link in reality.

Modelling signalized intersections. In the Highway Capacity Manual [14, p. 16-4] the capacity of a signalized lane C_i is defined as $C_i = f_i \cdot q_{S_i}$, where f_i is the percentage of green given to that lane and q_{S_i} is the saturation flow if traffic signals are switched off.

The extended Gawron model and the combined model can capture flows at signalized intersections by modifying the maximum permitted outflow c_{flow} according to green time of traffic signals. If the signal shows a color that allows vehicles to leave the link, flow is permitted with $floor(c_{flow})$ while $frac(c_{flow})$ is accumulated. If driving is not permitted, flow is stopped. Also, accumulation of the fractional part of c_{flow} is stopped. Thus, if driving is permitted for n timesteps, a maximum flow of $n \cdot floor(c_{flow}) + n \cdot frac(c_{flow}) = n \cdot c_{flow}$ is allowed. If $c_{flow} := q_{S_i}$ is used for signalized lanes, the model fulfils the requirements for signalized intersections from [14].

For the accuracy of the model it is important to stop accumulation of $frac(c_{flow})$ when driving is not permitted. This is illustrated in Fig. 3 that shows simulation results for a typical signalized link within an urban area, i.e. $c_{flow} = 2000veh/h$. For one hour, each second one vehicle enters the link. The green time is varied from 1 sec. up to the cycle time of 90 sec. and displayed on the x-axis of the figure. The y-axis shows the simulated number of vehicles leaving the link. Flow calculated by $C_i = f_i \cdot q_{S_i}$ is depicted by the green curve, while the red curve shows results of the simulation if flow accumulation is not stopped during red time. Compared to the calculated values, there is too much simulated flow. Furthermore, the curve shows some plateaus that are not specified by the model. Fig. 3(b) shows the same situation for a model that stops accumulation of $frac(c_{flow})$ during red time. One can neither see differences nor plateaus.

The combined model for signalized intersections is implemented within the MATSim framework. The next section presents simulation results of an illustrative real world scenario.

4. Illustrative application: City of Cottbus, Germany

The simulation scenario used in this paper is located in the federal state of Brandenburg, in Germany. It covers the area of the administrative district "Spree-Neiße" that is enclosing the city of Cottbus, plus the City of Cottbus itself.

Network & Population. The network is taken from OpenStreetmap (www.openstreetmap.org) data and consists of 4'417 nodes and 10'600 links. In the city of Cottbus live around 100'000 inhabitants while approx. 128'000 people reside in the administrative district Spree-Neiße. The synthetic population used for

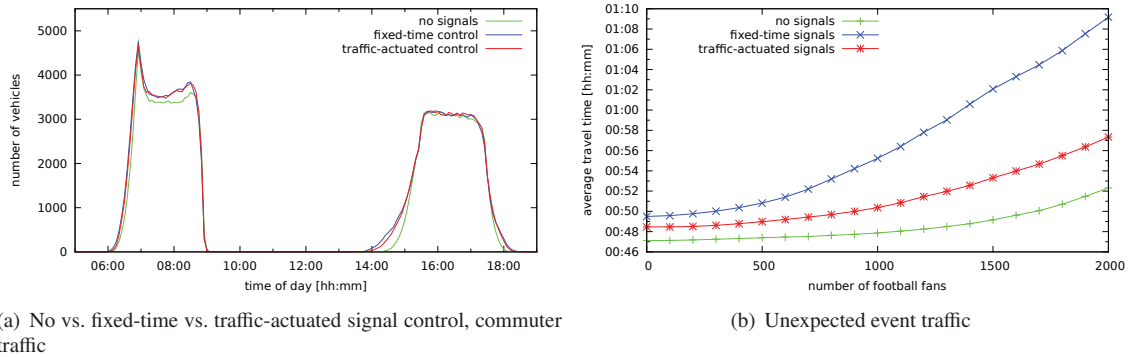


Fig. 4. Simulation results

the simulation is based on data taken from the German employment agency [15]. The data contains the number of commuters for each 2-tuple (home–work) of municipalities in Germany. Each commuter needs a geographic coordinate for his home and work activity. In combination with the “Corine Land Cover” landuse [16] provided by European Environmental Agency, activity locations are drawn randomly. The coordinate has to be in the area of the correct municipality. In case of a home activity, it must be located in urban fabric areas while in case of a work location, also industrial or commercial areas are allowed. The work activity must start between 7 and 9 am; initially every commuter starts at a random time in this interval. The modal split for the area of interest can be taken from the base year of [17] and is set to 55% car trips. This results in 33’479 commuters travelling by car.

Traffic Signals. Within the city area of Cottbus, fixed-time control schedules for 24 signal systems are available. All signal control plans have a cycle of 90 seconds. Green splits are taken from the currently running system, and offsets are optimized by [18]. Note that the demand used for optimization differs from the commuter demand used in this work. That reflects the typical case of optimized fixed-time control: Signals are optimized to a certain demand once, but while the demand changes over time the fixed-time control is not re-adjusted. The fixed-time data serves as input for the generation of base plans for a simple traffic-actuated control. Phase ordering and intergreens are taken over. For all phases, the initial green time is set to 5 seconds. If after 4 seconds vehicles are still approaching the signal, the green time is extended up to a maximum, which is set to the corresponding phase length of the fixed-time plan times 1.5. For details of the traffic-actuated control, see [19].

Run sequences. The simulation is run with the commuter population until the outcome seems stable, in this case for 500 iterations. In each iteration, 10 % of the commuters can choose new routes while another 10 % can vary their departure times. The only available mode is car. Then innovation is switched off, i.e. another 500 iterations are run that allow neither departure time nor route choice. Each commuter chooses out of a set of 4 plans using a multinomial logit model. See [20] for details. The above runs sequence is performed with three different signal control strategies: In a first simulation sequence, all traffic signals are switched off. This can be used as a lower bound for results concerning signal control since it assumes that vehicles are able to traverse a crossing without any accident, i.e. they are able to drive “through each other”. The next sequence uses a fixed-time setup. In the third, final, sequence, all traffic signals are controlled by the traffic-actuated control. All other parameters used for simulation are “default” values of the MATSim framework. For a detailed discussion, see, e.g., [20, 21].

Results. Simulation results for the commuter scenario are depicted in Fig. 4(a). The number of vehicles simultaneously on the road is plotted over the time-of-day. The results are quite similar for all signal control strategies.

A change of signal control has more effect if some unexpected traffic occurs on the network. In the last iteration of the run sequences, in addition to the commuters 0 to 2000 vehicles drive to the football stadium of Cottbus during the evening peak. Fig. 4(b) plots the number of football fans on the x-axis, and the average travel time of all travellers on the y-axis. Without any additional vehicles, the traffic-actuated signal control leads to a gain of approx. 1 min. per traveller. The more additional traffic is approaching the stadium, the more the traffic-actuated control saves travel time. In the case where 2000 additional vehicles are on the road, travel time savings reach ca. 15 min. per traveller.

The computation was run on an Intel Xeon Westmere Hexacore architecture using 1 core for the microsimulation. Without simulation of lanes and traffic signals, one execution of the traffic flow simulation takes on average 13 sec. computation time. If the lanes are switched on, one execution of the traffic flow simulation takes 14 sec. If additionally traffic signals are simulated it needs 16 sec. One complete run sequence (1000 iterations) takes 9 h and 12 min. The large number of iterations is necessary for a sufficient number of co-evolutionary learning iterations between the adaptive traffic signals and the adaptive agents.

5. Conclusion

This paper explains why for a multiagent modelling of interaction between travelers and traffic signals a fast traffic flow model is needed. For this purpose, several queue models for traffic flow are reviewed. It is discussed which use cases can be simulated with existing models. It turns out that none of them captures all use cases needed for the simulation of signalized intersections. Therefore, a combined model is proposed that captures advantages of existing approaches while deficiencies are avoided. It is explained why for certain road layouts a microscopic representation of turning lanes is needed in order to capture spillback correctly. This is especially important if traffic signals are simulated microscopically. The combined model captures flow for signalized intersections at an accuracy that is consistent with theory. The proposed model is tested in a real world scenario using a multiagent modelling approach. The results show that the model can be used to test traffic-actuated or adaptive signal control strategies in feasible computation times.

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