Amit Agarwal, Gregor Lämmel, Kai Nagel

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Modelling Backward Travelling Holes in Mixed Traffic Conditions using an Agent Based Simulation

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Abstract A spatial queue model in a multi-agent simulation framework is extended by introducing a more realistic behaviour, i.e. *backward travelling holes*. Space corresponding to a leaving vehicle is not available immediately on the upstream end of the link, instead the space travels backward with a constant speed. This space is named as 'hole'. The resulting dynamics resembles Newell's simplified kinematic wave model. Furthermore, fundamental diagrams from homogeneous and heterogeneous traffic simulations are presented. The sensitivity of the presented approach is tested with the help of flow density contours.

1 Introduction

Use of an iterative algorithm to determine the dynamic user equilibrium in simulators is common, but simulating large scale scenarios under reasonable time frame is rare [11]. A simple queue model is very helpful in traffic flow models due to its computational efficiency [11, 16]. In these models, vehicles move along a link at free flow speed until the end of the link. At the end of the link, if inflow is higher than maximum possible outflow (link capacity), a queue appears.

A simple approach is the point queue model in which vehicles are stacked on top of each other as vertical stack [19, 20]. In such models, the storage capacity is assumed to be infinite and therefore, queue length is zero, and spillover into other links does not occur. Shortcomings of the point queue model are the ignorance of the physical length of the queue, unclear interaction between links and missing intra-

A. Agarwal · Kai Nagel
Technische Universität Berlin, Sek. SG 12, Salzufer 17–19, 10587 Berlin, Germany
e-mail: amit.agarwal@campus.tu-berlin.de, nagel@vsp.tu-berlin.de

G. Lämmel
Institute for Advanced Simulation, Forschungszentrum Jülich, 52425 Jülich, Germany
e-mail: g.laemmel@fz-juelich.de

link congestion [19]. In urban settings spillover often occurs at many intersections in particular during peak hours. Spillover is considered in spatial queue models (see, e.g., [16]). This is achieved by assigning storage capacities to links based on length of the link and number of lanes. Spatial queue models observe those storage capacities by verifying the available space on the downstream link before allowing vehicles to enter it. Consequently, queues can spillover onto the upstream link(s).

In the *spatial* queue model, queuing occurs upstream of the bottleneck links as observed in real-life, but it is assumed that the space originating from leaving vehicles is available immediately at the upstream end of the link. Thus, in both point and spatial queue models, intra-link congestion is not incorporated.

Intra-link flow dynamics is described by the LWR model [12, 15] and by Newell's simplified kinematic wave model (KWM) [14]. Daganzo has proposed the cell transmission model (CTM) to solve the kinematic wave equation [6, 7]. A link transmission model (LTM) is introduced by Yperman [17]. In this model, traffic propagation is consistent with KWM.

Differences between point queue model, spatial queue model and cell transmission model under dynamic network loading condition are shown by [19]. The authors show that the point queue model considerably underestimates the dynamic network travel time. In addition, for heavily congested networks with spill-back, spatial queues without kinematic waves can also underestimate the impact of congestion. The limitations of the point and spatial queue models are shown also in a previous study by Frederix et al. [10] by comparing the results of toy scenarios with LTM.

One way to incorporate a KWM like flow dynamics into spatial queue models is the introduction of backward travelling holes (or gaps) [5, 8]. The present study continues this line of research by using the backward travelling holes in the spatial queue model.

In most of the developing economies, a variety of vehicles are prevalent on the streets which can be differentiated based on their static (dimension) and dynamic (speed, acceleration etc.) attributes. In this direction, the LWR model is extended analytically for mixed traffic by Zhang and Jin [18]. However, to avoid computational complexities, the present study focuses only on extending the queue model with holes for mixed traffic rather than addressing more general LWR model.

2 Modelling

Travel demand simulator The multi-agent transport simulation framework, MATSim [13] is used for all simulation experiments. The minimal inputs are physical boundary condition (the road network) and daily plans of individual travellers as an initial condition. Daily plans are loaded simultaneously using a network loading algorithm which is embedded into an iterative co-evolutionary algorithm [4]. The network loading algorithm of the MATSim framework is a so-called queue model [11, 16]. The queue model in MATSim allows spill back, thus, from here onwards in the present study, the queue model refers to the spatial queue model. In the present study, the queue model with holes is presented in detail. A brief introduction of the queue model with holes for seepage link dynamics is given in two previous studies [2, 1].

2.1 Race Track Experiment

A race track experiment is set up to to establish the relation between the three fundamental quantities of traffic flow, i.e. flow(q), density(ρ) and speed (v). A triangular race track is taken as experimental network in which agents keep travelling until a steady state is achieved [3]. Each side of the track is 1000 m long and the maximum allowed speed on all links is 60 km/h. Maximum flow capacity and density of each link are 2700 PCU/h and 133.33 PCU/km. Here, PCU refers to passenger car unit. Further, in order to check the behaviour of heavy vehicles, truck mode is also used. The maximum speeds and $PCUs$ of car, truck, motorbike, bike modes are assumed as 60, 30, 60, 15 km/h, and 1, 3, 0.25, 0.25 respectively.

Corresponding to each discrete density point and modal split, the number of agents on the race track are determined. These agents are allowed to run on the track until the fluctuations in the flow and speed of each mode are damped . This situation is referred to as steady state. Flow and speed corresponding to each density point are then recorded. The average values for each mode are recorded. Data is not recorded if a steady state is not achieved.

2.2 Queue Models without Holes

For reference, two link dynamics – namely, first-in-first-out (FIFO) and passing of queue model without holes – are presented here briefly.

2.2.1 FIFO

The queue model in MATSim follows the traditional *first-in-first-out* (FIFO) approach and processes the vehicle queue on each road segment (link) according to FIFO order. In the MATSim framework, a link l has a number of attributes e.g. link length ℓ_l, flow capacity c_{flow}, storage capacity $c_{storage}$, maximum allowed speed on the link $v_{l,max}$ etc. The flow capacity (link outflow) controls the maximum number of vehicles that can leave the link whereas storage capacity controls the link density i.e. maximum number of vehicles that can be placed on the link. For each entering vehicle with maximum vehicle speed $v_{v,max}$, an earliest link exit time (or free speed travel time, t_{free}) is computed as $= \ell_l/min(v_{l,max}, v_{v,max})$. Afterwards, the vehicle is added to the queue data structure, from where the vehicle is moved across the downstream intersection provided: (1) the vehicle has spent free speed time (t_{free}) on the link; (2) flow capacity of the link is available; (3) the downstream link has enough space. The queue model controls vehicles only at entries and exits, and never in between which makes it computationally efficient.

2.2.2 Passing

In order to simulate a traffic mix that consists of vehicles with different maximum speed ($v_{v,max}$) and physical characteristics, the MATSim queue model is modified by a passing queue [3] as follows:

1. A passenger car unit (PCU) equivalent is assigned to each vehicle type to consume the flow and storage capacities on the link.
2. The queue data structure is sorted based on the earliest link exit time (t_{free}). Thus, it allows faster vehicles to overtake slower vehicles.

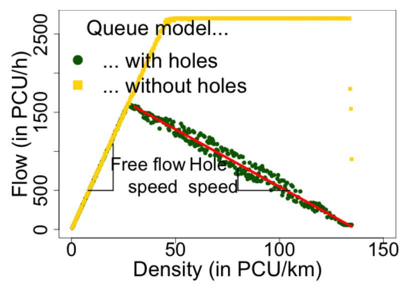
2.3 Queue Model with 'Holes'

In the FIFO and passing queue models, it is assumed that when a vehicle leaves the downstream end of the link, the freed space is available immediately on the upstream end of the link. As stated earlier, this is unrealistic; in real-life it takes some time for the free space to arrive on the upstream end of the link [5, 8]. Therefore, the present study continues by introducing backward travelling holes into the queue simulation. As the name indicates, in this approach, there are holes and they travel backwards, i.e. opposite to the direction of the traffic flow. The approach works as follows:

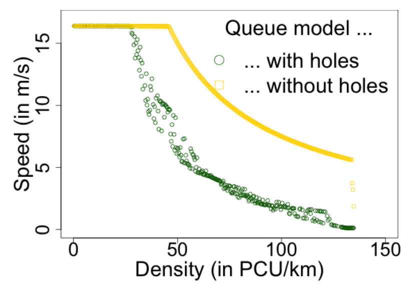
- Whenever a vehicle leaves the downstream end of the link, the space freed is called as 'hole'. Every hole has size equivalent to the PCU of the leaving vehicle.
- The space freed by the leaving vehicle is then occupied by the following vehicle and thus the hole propagates one step backward. This process continues until the free space (hole) arrives at the upstream end of the link.
- Consequently, the space on the upstream end of the link is not available instantly; instead it reaches after time t_{hole}. Each hole is equipped with upstream arrival time which is defined as $= \ell_l / v_{hole}$, where v_{hole} is the hole speed. This speed corresponds to the speed of the backward travelling kinematic wave in the KWM and mainly depends on the reaction time of the drivers.
- In this study, a constant hole speed of 15 km/h is assumed. This hole speed corresponds to a time headway of about 2 *sec* between two subsequent vehicles.
- After a certain density, no vehicle can enter the link until free space reaches the upstream end of the link. Therefore, in contrast to the queue model without holes in this approach, vehicles wait for the free space. Consequently, in addition to the existing outflow link capacity, an implicit inflow link capacity is introduced.

2.3.1 Comparison of with and without holes models

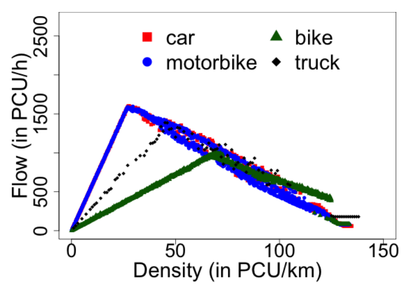
Fig. 1(a) and Fig. 1(b) show a comparison of both queue model approaches—with and without holes—for a car only simulation. In the free flow regime, the primary relationship between the three fundamental variables of traffic flow ($q = \rho \cdot v$) holds for queue models with and without holes. As already described in the Sect. 2.2.1, in the queue model without holes, the free space on the upstream end of the link is



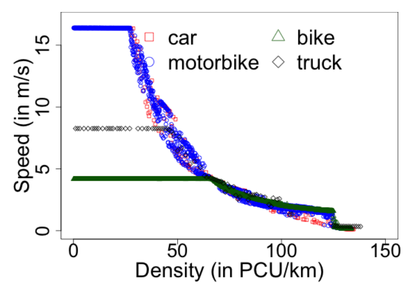
(a) Flow density plot for with and without holes queue models



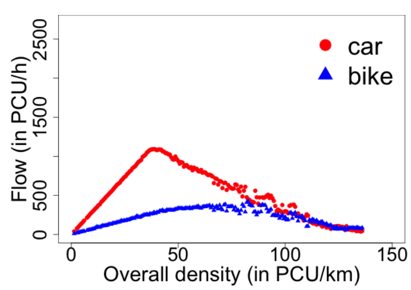
(b) Speed density plot for with and without holes queue models



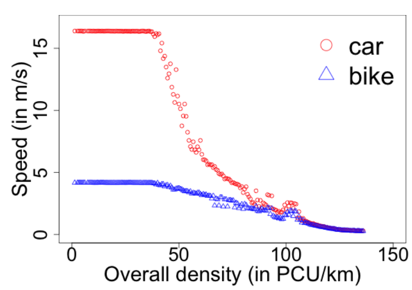
(c) Flow density plot from one mode simulations for with holes queue model (after [2])



(d) Speed density plot from one mode simulations for with holes queue model (after [2])



(e) Flow density plot for passing queue model with holes



(f) Speed density plot for passing queue model with holes

Fig. 1 Fundamental diagrams

available instantly and therefore, in capacity regime, a horizontal section is observed corresponding to the outflow capacity [16] and afterwards, at higher densities, this horizontal section joins together with a nearly vertically downward sloping congested branch (see golden points in Fig. 1(a)). In contrast, in the queue model with holes, the slope of the congested branch is reduced to the speed of the backward travelling holes. This branch is then met with the upward sloping free flow branch at a capacity below the outflow capacity. It can also be observed that the critical density at which speed starts decreasing is less for queue model with holes than in queue model without holes. Thus, the maximum flow for queue model with holes mainly depends on the backward travelling hole speed and maximum speed of the vehicle [9], this can be also verified from Fig. 1(c).

2.3.2 FIFO

Initially, FDs for single mode simulations, namely car, truck, motorbike, and bike are plotted (see Fig. 1(c) and Fig. 1(d)). Car and motorbike modes have different $PCUs$ and same speed therefore, when plotting density in PCU/km, the FDs for these two modes are similar. The FDs are not able to achieve the maximum flow due to implicit inflow link capacity as described in Sect. 2.3. Moreover, for truck and bike the maximum flow is even lower due to (1) lower maximum speed of these modes and (2) implicit inflow link capacity. The former can also be confirmed from FDs for queue model without holes, in which lesser bike speed result in lower maximum flow [3]. The maximum flow for truck and bike is achieved at a higher density than for car and motorbike due to lower maximum speeds.

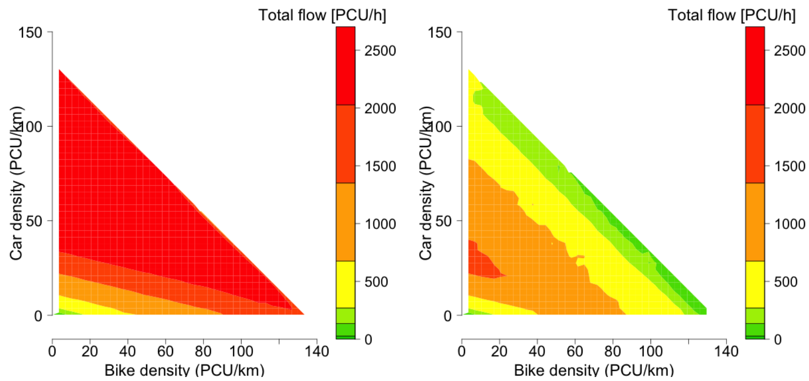
2.3.3 Passing

The queue model with holes is also applied to passing link dynamics. It is assumed that the reaction time of all vehicle types is same which results in a constant backward travelling hole speed for all vehicle types. In order to show the FDs for passing link dynamics in the queue model with holes, car and bike modes are simulated in equal PCU units. Resulting FDs are shown in Fig. 1(e) and Fig. 1(f).

Clearly, cars can overtake the slower bike mode. Car mode has the maximum flow at a lower density than bike because of slower speed of bike mode; this can be also verified from Fig. 1(c) in which maximum flow for bike mode occurs at a higher density.

3 Sensitivity

In order to check the sensitivity of the queue model with holes, flow density contours are plotted in Fig. 2 for different modal split variation of car and bike simulations



(a) Queue model without holes (b) Queue model with holes

Fig. 2 Flow density contours for car bike simulation and passing link dynamics.

on the race track. Fig. 2(a) and 2(b) show the flow density contours for the queue models with and without holes respectively. Clearly, at higher densities (diagonal values) the queue model with holes has a clearer jammed regime compared to the queue model without holes. Furthermore, it can also be observed that queue model with holes is not able to reach the link capacity due to the limited inflow caused by the backwards travelling holes.

4 Conclusion

This study extended spatial queue model in a computationally efficient multi-agent simulation framework by introducing a more realistic behaviour i.e. backward travelling holes. Since, in this concept, space freed by leaving vehicles is not immediately available on the upstream end of the link, the link inflow capacity is restricted implicitly. This eliminated the previously present unclear dynamics in jammed regime of the fundamental diagrams.

In order to validate the model, first, fundamental diagrams for one mode simulations were presented. Later, to test the mixed traffic behaviour, combination of car and bike were simulated and corresponding fundamental diagrams were presented. The sensitivity of the model was tested by comparing the flow density contours from with and without holes queue models. The presented queue model with holes is able to simulate mixed traffic more realistic and still is applicable to large scale scenarios.

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