# Modeling *seepage* behavior of smaller vehicles in mixed traffic conditions using an agent based simulation

Amit Agarwal, Gregor Lämmel

**Abstract.** *Seepage* is an important yet rarely modeled or quantified phenomenon in mixed traffic streams. It describes situations where smaller vehicles do not line up but rather "seep" through a queue of stationary or almost stationary vehicles. This contribution introduces *seepage* into an agent-based transport simulation model. In order to allow vehicles to seep, the traditional first-in-first-out queue model is modified such that in the free flow regime, faster vehicle can overtake slower vehicles and in the congested regime, slower vehicles can overtake faster vehicles. The model is validated with the help of fundamental diagrams. Its sensitivity is investigated by comparing the impact of different shares of smaller vehicles on the speed-density relation in mixed traffic streams. A case study of the evacuation of Patna, India under mixed traffic conditions with *seepage* demonstrates the overall approach.

**Keywords:** Seepage, Lane splitting, Lane sharing, Lane filtering, Mixed traffic, Agent-based modeling, Backward traveling holes, Evacuation

## 1 Introduction

Modeling complex heterogeneous traffic is a challenge for traffic planners since streets are full of variety of vehicles. These vehicles can be differentiated based on their static (physical dimension) and dynamic (speed, acceleration, power *etc.*) characteristics. The traffic in industrializing nations is different to the traffic in industrialized nations for at least following reasons (a) absence of lane discipline (b) common road space for motorized and non-motorized vehicles. The motorized vehicles include car, bus, truck, motorbike (motorcycles), scooters and, three-wheeler motorized rickshaws and non-motorized vehicles include bikes (bicycles), cycle-rickshaws *etc.* The presence of mixed traffic imply a different driving behavior than it is observed under homogeneous conditions. This contribution investigates one of such, so so-called *seepage* behavior, which predominantly exists in most of the industrializing nations.

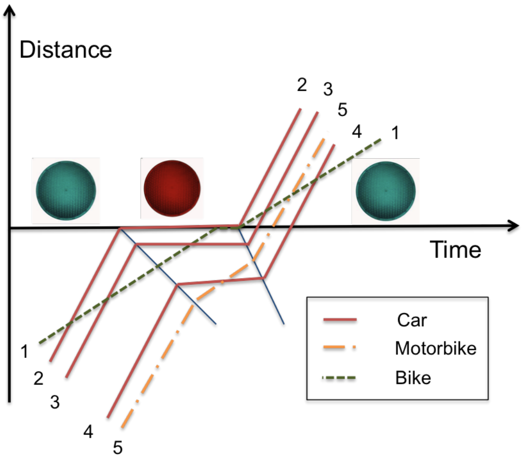
Due to its size and better maneuverability, smaller vehicles (motorbike, bike *etc.*) are less sensitive to the remaining traffic but in turn, affect flow of other vehicles considerably. Thus, during queue built up or at traffic signals, these vehicles move continuously across the gaps between stationary vehicles and come in front of the queues. In literature, this behavior is known as '*seepage* action' [1, 2], lane filtering (passing between stationary vehicles), lane splitting (passing between moving traffic) [3], and lane sharing [4]. Figure 1a shows *seepage* behavior of motorbikes and bikes at a traffic light in India, Figure 1b illustrates the differences between passing and *seepage* behavior, and Figure 1c exemplifies *seepage* of a bike and a motorbike at a traffic light. The bike (green dashed line) does not line up behind the cars when approaching the red traffic light, instead it seeps across the available gaps to come in front of the queue. Consequently, it departs before the cars when the traffic light turns green [1, 5]. Similarly, the motorbike (in orange dash-dot line) also seeps through the queue of cars. This behavior is a common praxis in the developing nations.

Studies that focus on the modeling of such traffic behavior are sparse. There exists, however, a large body of works that investigate pros and cons of it. Aupetit et al. [7] find that lane splitting is a systematic practice in the Paris region.

On the practical implementation side, from July 2014, lane filtering is legally approved in New South Wales, Australia under the *Road Transport Legislation Amendment (Lane Use by Motor Bikes) Regulation 2014* [8]. By allowing lane filtering, the authorities aim for less congestion and fewer rear end collisions.

A detailed overview on related studies is given in Agarwal and Lämmel [9]. The present work focus on the modeling of *seepage* in the context of a microscopic agent-based simulation.

**(a) Seepage of smaller vehicles at traffic signal [6].** **(b) Passing and *seepage*.**



**(c) Schematic of *seepage* at traffic signal. Reproduced after Oketch(2000) [1].**

**Figure 1: Seepage action**

Oketch [1] make an attempt to implement this behavior using lateral movement model. Nair et al [10] present an analogues multi-class ‘porous model’ to allow for *seepage*, in which traffic stream is considered as a porous medium and each vehicle type represents a class. Each vehicle class is considered to move through a series of pores and speed is determined by the availability of pores. In another study, Asaithambi et al [6] address the issue of *seepage* of motorbikes at traffic signals. The authors use exclusive stopping space for motorcycles (ESSM) in front of the queue at intersections and find it beneficial for all modal split except when the share of cars is dominant in traffic composition. Similarly, in Fan and Work [11, 12], develop a *seepage* model as a multi-class generalization of the cell transmission model. The models in the above studies are highly detailed models. Consequently, they are CPU-intensive and unsuitable for simulating large-scale scenarios. In previous work [9], introduce *seepage* functionality in a multi agent travel demand simulator MATSim [13]. The *seepage* is validated with the help of fundamental diagrams (FDs) and spatio-temporal plots. But the congested branch of the FDs for *seepage* remains unclear in [9]. Therefore, in the present study, the authors wish to extend and validate the *seepage* behavior with the help of a real-world scenario in addition to the fundamental diagrams.

A related situation is the evacuation of large urban areas, e.g. in the case of tsunamis[1]. As evacuees usually want to exit the affected area as fast as possible it is expected that *seepage* situations occur. This situation is addressed in a small evacuation experiment, where pedestrians are evacuated from an open ground to an exit zone (safe place) connected by a narrow street. The *seepage* behavior of pedestrians are studied under different mixing ratio of *stationary* cars [15]. The existing simulation framework (MATSim) is able to model the large evacuation problems [16, 17] in homogeneous traffic conditions. To the authors knowledge there exist no other simulation framework to model the *seepage* behavior under the highly dynamic conditions observed in real-world traffic in general and in particular in case of evacuations. With

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[1] See, e.g. [14] for a detailed overview of problems that arise when planing the evacuation of whole cities.

the help of the proposed approach, it will be possible to simulate large-scale evacuation scenarios under mixed traffic conditions and allowing *seepage* behavior. It is assumed that evacuation model would be more realistic from *seepage* as well. The results are quantified with the help of a real-world scenario of Patna, India.

The present study aims to; (1) extend the *seepage* queue model for multiple seep modes, (2) validate it with the help of the fundamental diagrams mainly in congested regime and test the sensitivity, (3) show the suitability for large-scale scenario simulation and and quantify the benefits.

The remainder of the paper is organized as follows. Section 2 illustrates the travel demand simulator and *seepage* queue model. Validation of the proposed model is done in Section 3 with the help of fundamental diagrams from different traffic mixes. Sensitivity analysis of the model is reported in Section 4. Further, a real-world scenario is presented in Section 5. In the Section 6, some additional aspects are discussed and finally, the study is concluded in the Section 7.

# 2 Modeling

## 2.1 Travel Demand Simulator - MATSim

The multi-agent transport simulation framework, MATSim [13] is used for all simulation experiments. Detailed information about the software has been published in several studies see e.g. [18, 19, 20, 21]. The minimal inputs for a simulation run are the physical boundary conditions (i.e. the road network) and daily plans of individual travelers.

In the MATSim framework, every person is considered as an agent who learns and adapts within an iterative process that is composed of following three steps: (1) Plans execution: selected plans of all agents are executed simultaneously using predefined mobility simulations in physical environment. A time step based queue simulation approach [22, 23, 24] is used for mobility simulation which is further modified in order to allow *seepage*. (2) Plans evaluation: In order to compare plans, executed plans are evaluated using a utility function. In this study, MATSim standard ‘Charypar-Nagel’ scoring function is used [25]. (3) Re-planning: A new plan is generated for some agents by modifying an existing plan’s attribute (departure time, route) using so called innovative strategies. The old plans are kept in the agents’ memories and can be selected by so-called non-innovative strategies later on. The new plan then is executed in the next iteration. By repeatedly performing the steps above, an iterative process is initiated. Innovation is used until a certain iteration and in the end few more iterations are run with non-innovative strategies only (i.e. plan selection), which finally results in stabilized simulation outputs.

## 2.2 *Seepage* methodology

Historically, MATSim simulations the traffic flow of vehicles by a *first in first out* (FIFO) queue model [22, 23]. Agarwal et al [26, 27] propose an *earliest-link-exit-time* approach that softens the strict FIFO order of the simulated vehicles. The earliest link exit time ($t_{earliest}$) on a link is given by Equation 1, where $\ell$ is length of the link, $v_{\ell,max}$ is maximum speed allowed on the link, and $v_{v,max}$ is maximum speed of the vehicle. The vehicles on the link are sorted based on the earliest link exit time and afterwards leave the link accordingly. Thus, this approach allows faster vehicles (lower $t_{earliest}$) to overtake (pass) slower vehicle s (higher $t_{earliest}$) in uncongested regime and in the congested regime i.e. after queue formation, the vehicles follow the FIFO model [27]. Hereafter, this model is referred as “passing queue model”.

$$t_{earliest} = \frac{\ell}{min(v_{\ell,max}, v_{v,max})} \tag{1}$$

In this contribution the passing queue model is further modified in order to allow passing of faster vehicles by slower vehicles in capacity and congested regime, which is referred to as *seepage* behavior as explained in Section 1. Thus, this work proposes the “*seepage* queue model”, which allow passing of slower vehicle by faster vehicles in the uncongested regime and vice versa in congested regime. The general approach for *seepage* functionality is similar to the approach in the previous study by Agarwal and Lämmel [9]. But, in the present study, the *seepage* queue model is improved and extended as shown in Algorithm 1.

(1) Instead of defining only one seep mode, the present study introduce the possibility to set multiple seep modes. Since, in the free flow regime, faster vehicles can overtake slower vehicle and therefore, passing is also allowed on the link. (2) If the flow on a link exceeds its flow capacity, a queue appears. Thus, in

**Algorithm 1: Schematic of *seepage* queue model (after Agarwal and Lämmel (2015) [9])**

```
Data: define one or more seep vehicle(s)
Input: A finite set of links $L = \{l_1, l_2, \dots, l_n\}$
for at every time step until simulation ends do
    for all links (i.e. $l_i \; \forall \; i \in (1,n)$) do
        if vehicle queued (i.e. $t_{actual} > t_{earliest}$) then
            for all queued vehicles do
                if queued vehicle = seep vehicle then
                    send queued vehicle to front of queue;
                    break and go to next link;
                else
                    go to next queued vehicle;
        else
            go to next link;
```

the simulation framework, the agent is queued if the time step ($t$) exceeds the precomputed earliest link exit time ($t_{earliest}$) of the agent on the link. (3) In the next step, just before a vehicle is about to leave the link, the vehicles whose earliest link exit time has passed (basically queued vehicle), are identified. (4) For identified vehicles, a seep mode is searched and if it is found then it is pushed to the front of queue and, afterwards, the front vehicle (seep mode) leaves the link depending on the flow capacity of the current link and the storage capacity of the next link. (5) If a seep mode is not found in the queue, flow dynamics remain unaltered i.e. first vehicle in queue leaves the link if flow and storage capacities of the involved links are not violated. Seepage is not allowed between two vehicles of same type.

# 3 Fundamental diagrams

In this section, the *seepage* queue model is validated with the help of fundamental diagrams (FDs). Car, motorbike and bike travel modes are used for the mixed traffic experiments in the present study. For simplicity, the passenger car units (PCU) and speeds of these modes are taken from the previous studies [26, 27] and are shown in Table 1.

**Table 1: Travel mode parameters.**

| Travel Mode | PCU | Speed ($m/sec$) |
|---|---|---|
| Car | 1 | 16.67 |
| Motorbike | 0.25 | 16.67 |
| Bike | 0.25 | 4.17 |

## 3.1 Experiment set up for FDs

In order to plot FDs, a triangular race track network is used as shown in Figure 2. The race track network is the same as in previous studies [9, 26, 27] The length of the links in the network is 1000 $m$ each. Maximum flow capacity and density for each link are 2700 $PCU/hr$ and 133.33 $PCU/km$ respectively. All agents depart from left and continue traveling on the track until flow becomes steady and afterwards agents arrive on right.

## 3.2 FDs with backward traveling holes

The FDs for the FIFO queue model and passing queue model that are presented in the studies by Agarwal et al [26, 27] do not display the typical triangular shape, since the congested branch of the FD is not well reproduced. For that reason the concept of backwards traveling holes is introduced into the *seepage* queue

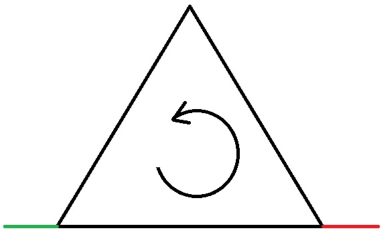


**Figure 2: Triangular race track network.**

model. The backwards traveling holes approach mimics the simplified Kinematic Wave Model (KWM) [28, 29, 30]. However, a true consistency with the theory is unclear since mixed-traffic and *seepage* is beyond the “classical” KWM. The backwards traveling holes approach works basically as follows.

Every time a vehicle leaves the downstream end of a link the space freed by the leaving vehicle forms a gap or ‘hole’. This ‘hole’ is not available instantly on upstream end of the link instead it is subsequently occupied by the following vehicles until it reaches the upstream end of the link. Consequently, it takes some time for the hole (space) to reach to the upstream end of the link [31, 32]. Therefore, after a certain density has passed, no vehicle can enter the link until free space reaches the upstream end of the link and thus, the holes effectively introduce an inflow link capacity, in addition to the already existing outflow link capacity. Holes are distinguished by vehicle types. Therefore, two attributes are assigned to each hole: (1) size of the hole, which is same as the PCU of the leaving vehicle and (2) speed of the hole, which is a constant for all vehicle types. Thus, each hole has precomputed times of arrival on the upstream end of the link. In the present study, the backward traveling hole speed is assumed to 15 $km/hr$ which corresponds to a time headway of about 1.8 *sec* between two subsequent vehicles.

## 3.3 FDs for only one seep mode

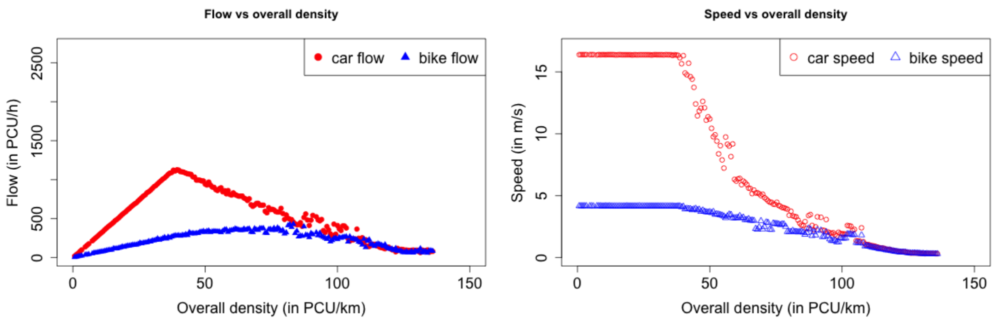
For the reference purpose, the initial unclear *seepage* FDs from the previous study [9] are also presented here. Figure 3 shows the different FDs from passing and *seepage* queue models for equal model split (in $PCU$) of car and bike.

Figure 3a and Figure 3b show the FDs for passing and *seepage* queue models respectively. In Figure 3a, the left branch of the FDs determined by the free flow (maximum) speed of the vehicle and maximum allowed speed on the link (see Equation 1) and the right branch is determined by the fixed speed of the holes. The branches of FDs in free flow regime in Figure 3a and in Figure 3b are same since, until the capacity regime is reached, the slope of the flow density curve is given by the minimum of maximum allowed link speed and maximum speed of vehicle (see Equation 1). After that, flow starts decreasing until the flow becomes zero thus capacity regime together with the jammed regime govern the link dynamics during congestion. The speed-density plot shows the variation in the speed of the vehicle over total density. In the free flow regime, speed of car mode and speed of bike mode are equal to their maximum speeds and decrease afterwards.

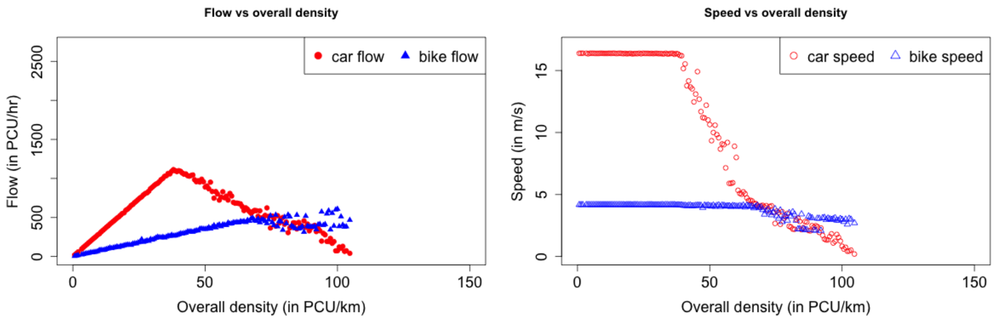
From Figure 3b, it can be observed that bike flow increases until a density of about 110 $PCU/km$ and bike speed reduces marginally slightly after free flow regime. On the contrary, car flow and speed is approaching zero at a lower density compared the passing queue model. But, data points corresponding to bike densities higher than 110 $PCU/km$ are not observed due to the flow dynamics induced by the holes for higher densities. Data points are only collected if flow and speed fluctuations are dampened. The fluctuations in speed and flow are inspected when a vehicle leave the base link (see Figure 2). At higher densities, more bikes are in the queue and due to *seepage* behavior, only bike leaves the link. Since, car do not leave the link, car flow has higher fluctuations and subsequently, no data point is recorded for such states. This explains the missing data points after a density of 110 $PCU/km$.

## 3.4 Restricted *seepage*

To get a more clearer congested branch of the FDs, the *seepage* behavior is restricted as shown in Algorithm 2. Since, all smaller vehicles do not perform *seepage* and therefore, the following process is reason-



(a) Car bike passing.



(b) Car bike *seepage*.

**Figure 3: Fundamental diagrams for passing and *seepage* for car, bike simulation [9].**

**Algorithm 2: Alternative (in red) schematic of *seepage* to get data points at higher density**

```
Data: define seep vehicle
Input: A finite set of links $L = \{l_1, l_2, \dots, l_n\}$
for at every time step until simulation ends do
    for all links (i.e. $l_i \; \forall \; i \in (1,n)$) do
        if vehicle queued (i.e. $t_{actual} > t_{earliest}$) then
            for all queued vehicles do
                if queued vehicle == seep vehicle then
                    if $m \leq 4$ then
                        m++;
                        send queued vehicle to front of queue;
                        break and go to next link;
                    else
                        m = 0;
                        go to next link;
                else
                    go to next queued vehicle;
        else
            go to next link;
```

able. After every four[2] bikes, the first vehicle (car or bike) in the queue is allowed to leave. The resulting FDs are shown in Figure 4. Now, comparing Figure 3b and Figure 4, it is more clear that, due to seepage, bike flow and speed start decreasing at a density higher than in the passing queue model. Thus, even after the *seepage* behavior is restricted, the speed of bike in the *seepage* FD remains equal to the maximum speed of bike up to a density of 65 $PCU/km$. Clearly, in case of passing behavior (see Figure 3a), flow

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[2] In order to show the congested regime of flow-density curve of bike, this number is assumed to 4 (equivalent to 1 $PCU$), however, the true value need to be calibrated from the scenario specific survey data.

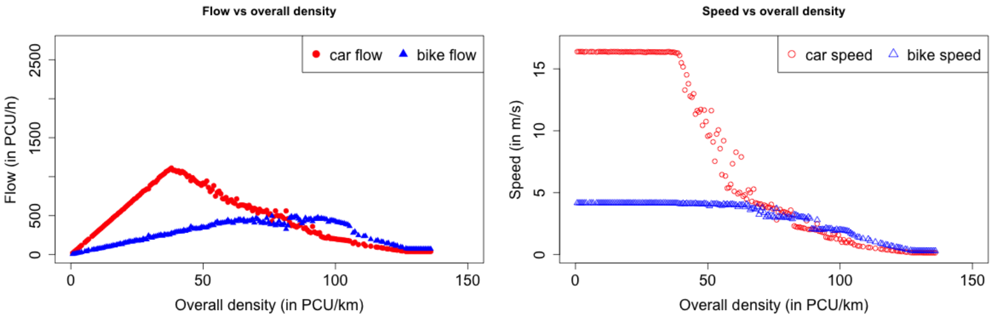
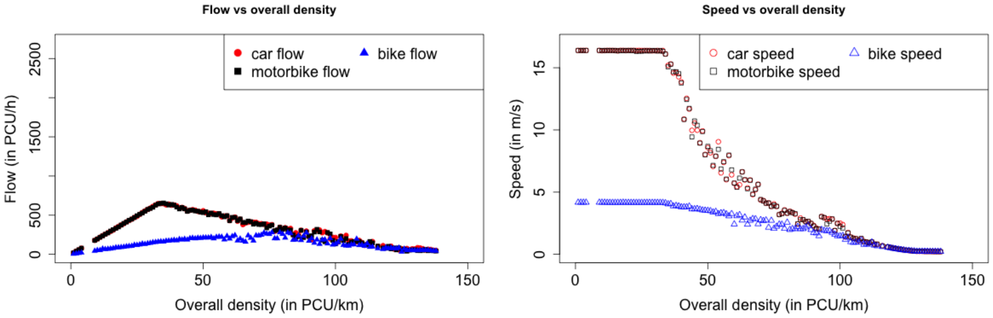
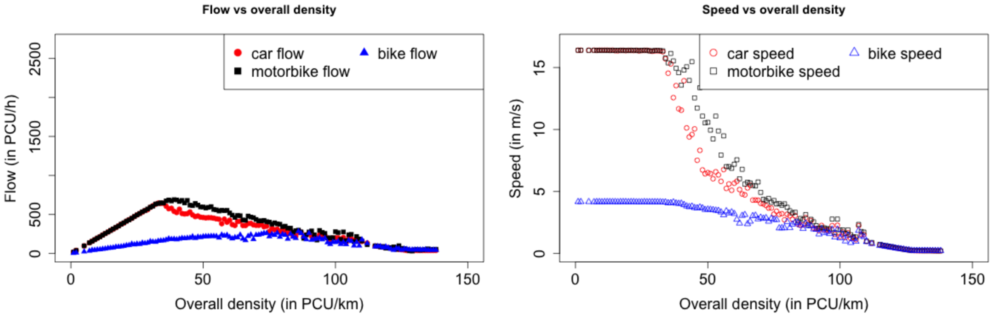


**Figure 4: FDs for *seepage* queue model according to Algorithm 2. Car and bike modes are taken in equal modal split and bike is considered as seep mode.**



**(a) Car bike passing.**



**(b) Car bike *seepage*.**

**Figure 5: Fundamental diagrams from passing and *seepage* queue model for equal modal split (in PCU) of car, motorbike and bike simulation. Bike and motorbike are assumed as seep modes.**

characteristics of bikes and cars are affected by the presence of each other. On the contrary, in the *seepage* behavior (see Figure 4), the flow characteristics of bikes is marginally affected by presence of cars but flow characteristics of cars is significantly affected by presence of bikes and thus producing a behavior similar to what is observed in reality. These results are in line with observations on traffic in developing nations where mixed traffic has smaller vehicles in abundance as shown in Fig. 1a.

## 3.5 Multiple seep modes

Since, due to its small size, motorbike also has high maneuverability and therefore can show the *seepage* behavior as shown in Figure 1a. Therefore, in the present study, FDs are also plotted for mixed traffic situation where bike and motorbike both perform *seepage* behavior.

Figure 5 shows the FDs for passing and *seepage* queue model where car, motorbike and bike modes are simulated in equal modal split (in PCU). Motorbike and bike are defined as seep modes and Algorithm 2 is used to generate FDs. Again, similar to the Figure 3a and Figure 3b, the left branch of the FDs for car and motorbike are same because this branch represents free flow regime where the speed of the vehicle is determined by Equation 1. The speed of car and motorbike are same and therefore these two vehicles have overlapping data points in FDs for passing queue model (see Figure 5a). Due to slower maximum speed of the bike mode, the left branch of the FD has a flatter slope as the left branch of the FD for car and motorbike mode. The FDs for *seepage* queue model are shown in Figure 5b. Clearly, after the density exceeds the free flow regime, the flow and average speed of car is smaller than flow and speed of motorbike respectively because motorbike can seep now. Similarly, bike mode also perform *seepage* but due to its lower maximum speed, only a marginal effect can be observed in the FD. Therefore, if the modal share of faster seep mode is significant, the slower seep mode is not able to seep significantly and therefore it is not captured in the FDs.

# 4 Sensitivity

The most of the FDs shown in Figure 3 are plotted for equal modal split and therefore, it is important to see the sensitivity of the *seepage* behavior. Hence, a sensitivity test is conducted to test the *seepage* behavior for different bike shares using Algorithm 2. Experiment are performed on the same race track (see Figure 2). Two modes, car and bike are used for the simulation runs with different bike shares in the traffic mix. The speeds of bike and car mode are plotted against densities of car and bike respectively (see Figure 6).

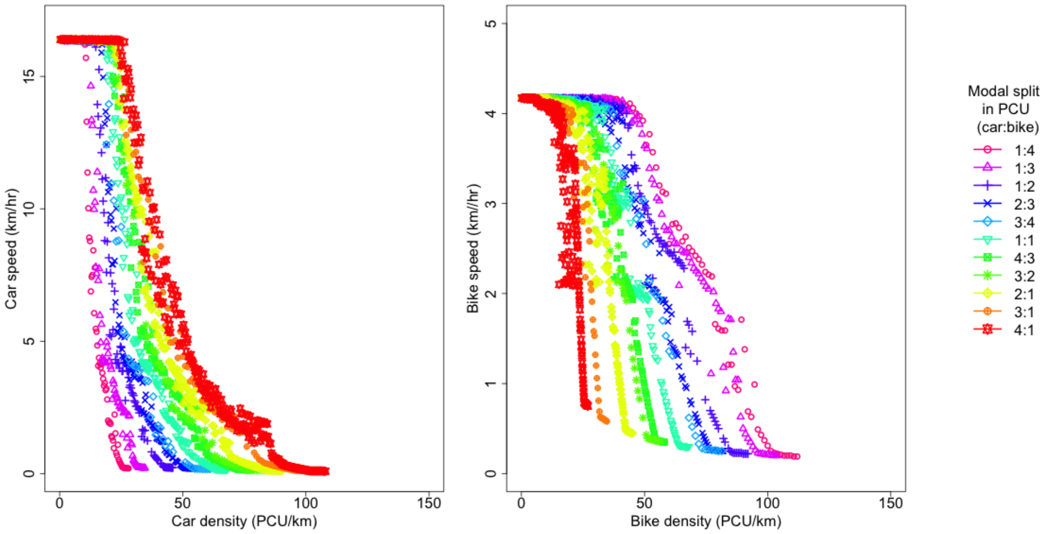


**Figure 6: Variation in car and bike speed for different modal split in PCU.**

From the Figure 6, one can observe that an increase in the bike share decreases the density at which the speed of car starts decreasing and vice-versa it increases in the density at which the speed of bike starts decreasing. This happens because, at a higher bike share, bike appear in front of the queue more often and consequently *seepage* of bike take place. Hence, change in the speed of bike is marginal until higher density. Therefore, the resulting plot is plausible and similar to the behavior observed in reality.

# 5 Application

This sections describes the application of *seepage* in a large-scale transport simulation. The proposed *seepage* queue model is applied to a real-word scenario of Patna, India. The scenario is about an evacuation of heterogeneous traffic where *seepage* behavior is present.

## 5.1 Real world evacuation

As described previously, in the Section 1, a small experiment is conducted within the project *Last–Mile–Evacuation* [14]. The experiment study the evacuation of pedestrians using *seepage* action while moving through a group of stationary cars [15]. This is a static example but with the help of the proposed model, the evacuation of mixed traffic with *seepage* behavior is possible and presented next.

The following discusses the application of the proposed model a real-world evacuation scenario of mixed traffic with *seepage* behavior. The objectives of presenting this real-world scenario is to show and to quantify the influence of *seepage* for disaster management. The approach is useful for simulating large-scale evacuations (e.g. in case of tsunamis or forest fires) in densely populated areas where *seepage* is exacted to take place.

***Inputs*** The initial scenario is the same as in the study of Agarwal et al [26] and therefore described here briefly. The input network consist of 3505 nodes and 7542 links. A disaster prone area is identified as evacuation area. The aim is to evacuate all the persons inside this area. The network is connected with some exit links which lead to a safer location.

The location and travel mode of the persons are taken from the Patna comprehensive mobility plan [33]. For simplicity, it is assumed that all persons starts evacuating simultaneously as soon as warning is announced and all persons starts evacuating from their home location.Thus in the simulation run, all people inside the evacuation area are considered for evacuation. Assuming everyone starts at once is a conservative assumption, since it would lead to a high initial load onto the network and thus to high densities resulting in a lower throughput (cf. FDs in Figure 3) compared to widely distributed departure times. A study that investigates the influence of departure time distribution on the overall evacuation performance is presented in [34]. In absence of travel schedule for public transport (PT), PT mode is not considered in the simulation. The walk mode can not be simulated using regular vehicular traffic model and therefore skipped in the simulation. Thus, similar to the previous study [26], car, motorbike and bike modes are considered in the simulation. Overall about 1% sample size is taken. Though, both motorbike and bike can be assumed as seep modes but for the simpler analysis purpose, only bike is considered as seep mode in this simulation run.

***Simulation set up*** Two simulation runs are considered, one corresponds to passing and the other to *seepage* behavior. Simulations are run for 100 iterations. Until the 75 iterations, 10% of agents are allowed to change their route and remaining agents until 75 iteration and all agents after 75 iteration, select a plan from their generated choice set according to probability distribution which converges to multinomial logit model [35]. In the $0^{th}$ iteration, basically the shortest path is assigned to each agent between its origin and destination. Afterwards, agents learn and adapt to the system as described in the Section 2.1. Finally, the outcome of the last iteration shows the routes corresponding to an approximately Nash equilibrium (NE). Therefore, based on the agents' behavior, results are also analyzed for two cases, namely (1) Shortest path (SP) (2) Nash equilibrium (NE).

***Results*** Table 2 shows the comparison of average trip time from two simulation runs and for both cases. Clearly, as expected, the average SP trip time is significantly higher than for NE in both simulation runs. Interestingly, the effect of *seepage* behavior can be observed in the $0^{th}$ iteration only. For the SP case, the average trip time for bike with *seepage* behavior is about 13% less than the average trip time with passing behavior only. Consequently, due to *seepage* of bike, the average trip time for car and motorbike is increased.

In the NE case, the average trip time for each mode is significantly shorter than the average trip time in SP case for both simulation runs. Furthermore, in the *seepage* run, bike can overtake car and motorbike in congested regime thus bikes are faster and therefore average trip time of bike is 17.6% less than the average trip time for passing run. As a consequence of *seepage* of bike mode, average trip time of car and motorbike is 38.5% and 40.5% higher than the average trip time for passing run respectively. Interestingly, in the end, the total clearing time to evacuate all agents stays the same when *seepage* is enabled.

**Table 2: Comparison of passing and *seepage* evacuation runs for Patna.**

| Travel mode | Number of evacuee | Avg trip time passing [*min*] | | Avg trip time *seepage* [*min*] | |
|---|---|---|---|---|---|
| | | SP | NE | SP | NE |
| Car | 168 | 301.94 | 123.42 | 368.42 | 170.91 |
| Motorbike | 1266 | 329.57 | 152.46 | 451.76 | 214.33 |
| Bike | 3921 | 382.73 | 178.47 | 333.47 | 147.00 |

***Evacuation progress*** Figure 7 shows the evacuation progress for both simulation runs and for both cases. Since, only bike is allowed to seep, car and motorbike modes are combined together and referred to as fast mode whereas bike is referred to as slow mode. Firstly, as expected, NE leads to shorter evacuation times compared to SP for both simulation runs and both types (slow and fast) modes. The slow mode in the *seepage* run also show the same trend. This is in line with the literature [16]. In terms of policy making

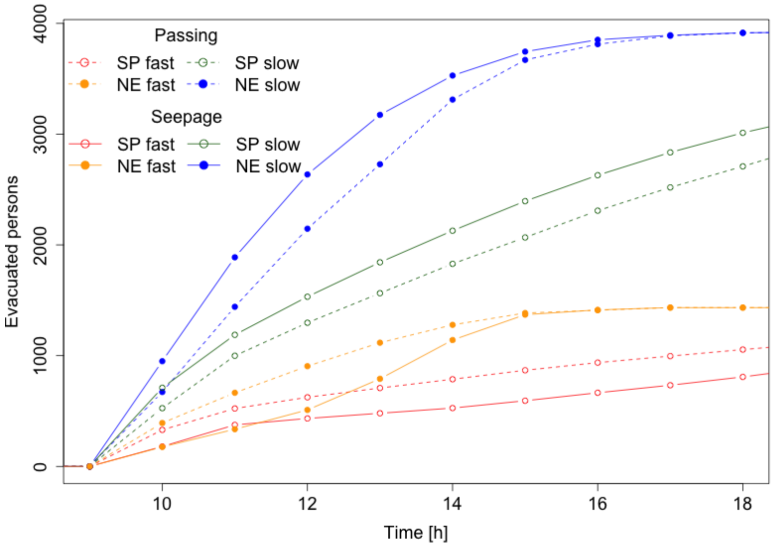


**Figure 7: Comparison of evacuation progress. Fast refer to car and motorbike whereas slow refer to bike.**

this would mean the shortest path solution does not take congestion into consideration and thus it is not a feasible solution. But, on the contrary, due to *seepage* of bike, fast modes are stuck and therefore, in the fast mode of *seepage* run, initially, number of evacuated persons for NE (solid orange circles) is slightly lower than SP (hollow red circles). Furthermore, *seepage* has led to higher evacuation rate for bike mode and to lower rate for fast modes (car and motorbike). In the afternoon hours, fast modes in the *seepage* run catch up and become almost the same as for the passing run. Overall, *seepage* has no negative impact in terms of evacuation rate.

# 6 Discussion

In the present study, *seepage* of smaller vehicles bike (bicycle) and motorbike is studied. But, the same approach is applicable for any type of vehicle type across the world. Sometimes, car seep between the truck on a multi-lane highway. Seepage plays also an important role in situation where ambulance vehicles or other fire engines need to seep through large pedestrian crowds. This situation happens for example during large music festivals or other public events. In those situations the seep mode is not assigned to the smaller vehicle, instead the smaller “vehicles” (i.e. pedestrians) give space to the large vehicles (i.e. ambulances). Albeit those situations seem to be quite different from the *seepage* observed on road networks, it seems to be reasonable to apply a similar approach as the one that has been proposed in this contribution. The general applicability of queuing models to pedestrian traffic has been discussed in earlier works [36].
As shown in the Figure 1b, during *seepage* in practical situations, bike (seep mode) do not occupy additional space instead use the space between the two cars in the same lane which in turn can relief the additional storage space. This additional space can enhance the saturation flow and overall result in lesser clearing time for evacuation scenarios. This functionality is not considered in the present study, but it will be implemented in future studies.

# 7 Conclusion and Outlook

In order to simulate the heterogeneous traffic close to reality, this paper presented a so called “seepage” behavior in an agent-based simulation framework. This is a common praxis in most of the developing and some of the developed nations. Due to the smaller size and easier maneuverability, smaller vehicles (bike, motorbike) creep across the gaps between the stationary or almost stationary vehicles. The fundamental diagrams for various simulation runs are demonstrated for the validation of the proposed model. The dynamics of the queue model in congested regime was unclear and therefore the concept of backward traveling holes is used which introduced a link inflow capacity implicitly. The models sensitivity is tested by varying the share of bikes in a mixed traffic situation. A higher share of bikes leads to a higher frequency of *seepage* actions and thus, seep mode retain its maximum speed even for higher densities.

Furthermore, the proposed *seepage* queue model has been applied to a real-world scenario of Patna, India for the evacuation modeling in mixed traffic conditions. The passing and *seepage* queue model are compared based on this scenario. Clearly, the *seepage* behavior resulted in a significant decrease in average trip time for bike mode and in a increase in average trip time for car and motorbike modes. Overall, the total travel time for the *seepage* and passing simulation run were more or less same.

In future, the proposed model will be tested with with traffic under regular conditions and for the system optimum solution for evacuation modeling, similar to Lämmel and Flötteröd [37], but for heterogeneous traffic conditions. Research into the application of the KWM theory to mixed mode traffic with *seepage* will be a future topic as well.

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