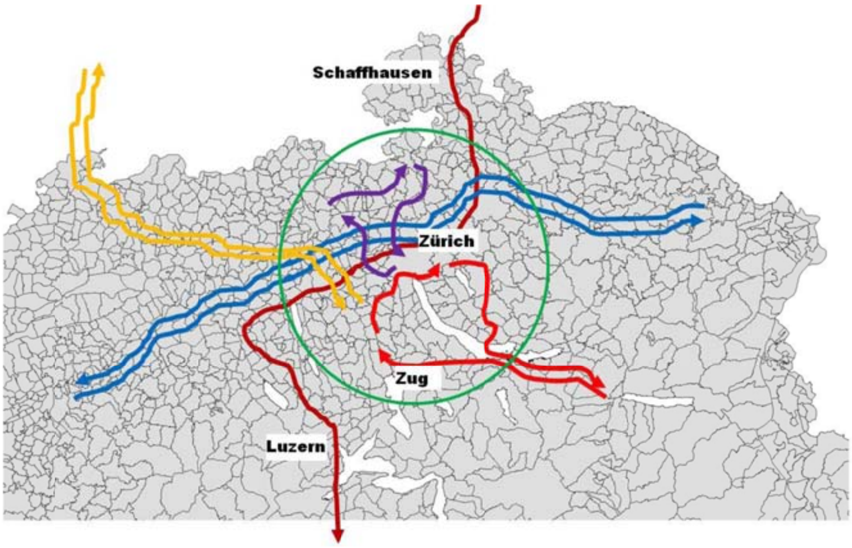

Investigation of Macroscopic Fundamental Diagrams in Urban Road Networks Using an Agent-based Simulation Model

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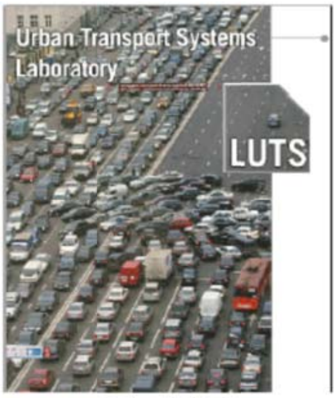
Conference paper STRC 2011



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Investigation of Macroscopic Fundamental Diagrams in Urban Road Networks Using an Agent-based Model

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May 2011

Abstract

Congestion pricing is considered an effective management policy to reduce traffic congestion in transportation networks. To study congestion pricing schemes in urban networks, one would require a simulation model which can represent demand elasticity and traffic supply dynamics. Two main inadequacies exist in current simulation models. Firstly, the traditional traffic simulators with car-following lane-changing and route choice models consider traffic demand as input, i.e. inelastic to level of congestion conditions. Secondly, in traditional congestion pricing models with elastic demand, the utilized network supply curve is not consistent with the physics of traffic and dynamics of congestion and queues. Also, many of these models are assuming deterministic and homogeneous population characteristics. This might result in non-optimal estimated tolls. Agent-based models are possible solutions for representing demand elasticity. This is because heterogeneous travelling agents are used in the models, (i) each agent has an individual utility function, (ii) each agent has individual value of travel time savings and (iii) one agent's behaviour affects other agents' decisions. For network supply modeling, it has been broadly shown through field tests and traffic simulations that traffic in large urban regions can be modelled dynamically at an aggregate level, as expressed by a Macroscopic Fundamental Diagram (MFD). If the output of an agent-based model shows the property of the MFD, it would be interesting to develop a dynamic network-wide congestion pricing schemes controlled by this macroscopic tool. Therefore the goal of this paper is to investigate whether an agent-based simulation model produces results consistent with the physics of traffic and whether a MFD can be observed.

Several case studies are done on Zurich urban road network in the multi agent-based traffic simulator MATSim. Results show that the productions of MATSim are consistent with the physics of traffic flow at both microscopic and macroscopic levels. Besides, MATSim is able to reproduce similar traffic phenomena such as network hysteresis loops which have been observed in previous work from real experiments and traffic simulations.

Keywords:

Agent-based model, demand elasticity, urban network, MFD, MATSim, congestion modeling

1. Introduction

To alleviate traffic congestion in cities, congestion pricing has been proposed by researchers and policy makers. The intention is to change travellers' behaviour, such as departure time or route choice, to reduce congestion by charging them for the external costs they create. There is a vast literature on link-based or bottleneck-based congestion pricing. In practice, these pricing schemes are costly and difficult to implement since tolls need to be decided for each link. Instead of charging in individual separate links, cordon- or area-based pricing schemes has been developed and applied, in which a pricing scheme is implemented only on the links of the border of a region/network. A comprehensive literature summary of these congestion pricing models can be found in Yang and Huang (2005). In most models, demand elasticity is realized by introducing cost to alter travellers' behaviour. For example, in Vickrey's model (1969) a traveller experiences a delay cost of waiting in the queue and a penalty, "schedule delay", which is the difference between the actual time passing the destination and the desired time; accordingly, the traveller may adjust his departure time to avoid highly congested periods. Equilibrium obtains when no individual has an incentive to alter his departure time. The common inadequacy of these models is that: although most congestion pricing models take demand elastic to cost of supply, travellers are assumed to have the same utility function towards cost. From this perspective, agent-based modeling can model demand elasticity in a more realistic way. This is because of its capability (i) in modelling individual components, such as each agent has his own utility function of performing an activity, (ii) in differing traveller's behaviour towards costs and savings by giving travellers different values of travel time savings (VTTS) and (iii) in modelling the interactions of agents in complex network, such as one agent's decision affects the others' (Zhang, et al., 2008). By utilizing agent-based models for congestion pricing, not only behaviour changes can be better captured but also the issue of equity can be investigated.

The traditional network supply curve for congestion pricing modeling, relating input demand to average travel cost, is not consistent with the physics of traffic (Geroliminis and Levinson, 2010). This is because for a given average flow, i.e. desired demand over a period of time, the total cost expressed in delay terms (i) is sensitive, during congested conditions, to small variations of flow within the given period and (ii) depends on the initial state of the system and the level of congestion. It has been broadly shown through simulation and field experiments (Geroliminis and Daganzo, 2007, 2008) that plots between pertinent variables (flow, speed, delay) on a spatially disaggregated level, i.e. in one link in a network, are very chaotic and do not follow a well-defined curve. The main reason is that, at a link level, traffic systems are not in steady-state conditions. Thus, the estimated congestion toll based on idealized versions of these curves may not be optimal and the system may be either still congested (if under-priced) or very uncongested (if over-priced). According to the same work, a Macroscopic Fundamental Diagram (MFD) model can describe the collective behavior of urban networks, without the detailed knowledge of conditions in individual links. This is observed and concluded with real-data of a 10km^2 region in the Yokohama city center and a microscopic traffic simulation of San Francisco downtown region.

To test the effectiveness of different congestion pricing schemes such as cordon- or area-based pricing, one would require a simulation model which can represent demand elasticity and network production dynamic as mentioned above. If the output of an agent based model is also able to represent collective traffic behavior and macroscopic traffic flow dynamics as this expressed by MFD, then it would be interesting to utilize this macroscopic tool to develop and control a dynamic congestion pricing scheme in the agent-based model. Therefore, as a preliminary study on congestion pricing in agent-based model, this paper investigates the existence of the MFD in an agent-based simulator. We will prove the existence of MFD in MATSim, a multi-agents based simulator which was developed jointly at ETH Zurich and the TU Berlin (more information about MATSim please refer to www.matsim.org).

The content of the paper is structured as the following: we describe the main features of the MFD model in Section 2. The basic principles of the MATSim simulator will be explained in Section 3. In Section 4 we present our methodology on demonstrating the existence of MFD. In Section 5 we show our results and findings on MATSim's production. While in Section 6 we draw conclusions and propose further research directions.

2. The Macroscopic Fundamental Diagram

In this section, we describe the important features and findings of the MFD model. Daganzo (2007) and Geroliminis and Daganzo (2007, 2008) proposed and proved the Macroscopic Fundamental Diagram model, showing that uniformly congested urban neighbourhoods approximately exhibit a relation between the numbers of vehicles in the neighbourhood (accumulation) to the neighbourhood's average circulation flow (vehicle kilometres travelled divided by the total length of roads). This happens even though the flow versus density plots for individual links (known as Fundamental Diagram) exhibit considerable scatter, so that MDF is a good description of network property and network supply curve. It is proved by using a micro-simulation of the San Francisco business district in the United States and a field experiment in downtown Yokohama in Japan. Figure 1 shows some findings of the experiment in Yokohama with time resolution 5min. It is observed that when the somewhat chaotic scatter-plots of speed vs. density from individual fixed detectors were aggregated for a 10km^2 region, the scatter nearly disappeared and points grouped neatly along a smoothly declining curve. This observation is by comparing Figure 1a with Figure 1d-1f. The same references also showed that (i) the MFD is a property of the network itself (infrastructure and control) and not of the demand, i.e. the MFD should have a well-defined maximum and remain invariant when the demand changes both with the time-of-day and across days. Figure 1c shows the differences in demand pattern. Note that (i) may vary if the O-D pattern of demand changes significantly, e.g. due to an event or evacuation; (ii) the space-mean flow, is maximum for the same value of density of vehicles or average speed, independent of the origin-destination tables; (iii) the average trip length for the study region is about constant with time, i.e. the total outflow vs. density curve is a scaled up version of the Figure 1b and (iv) the MFD can be estimated accurately using existing monitoring technologies (e.g. detector data, GPS etc.).

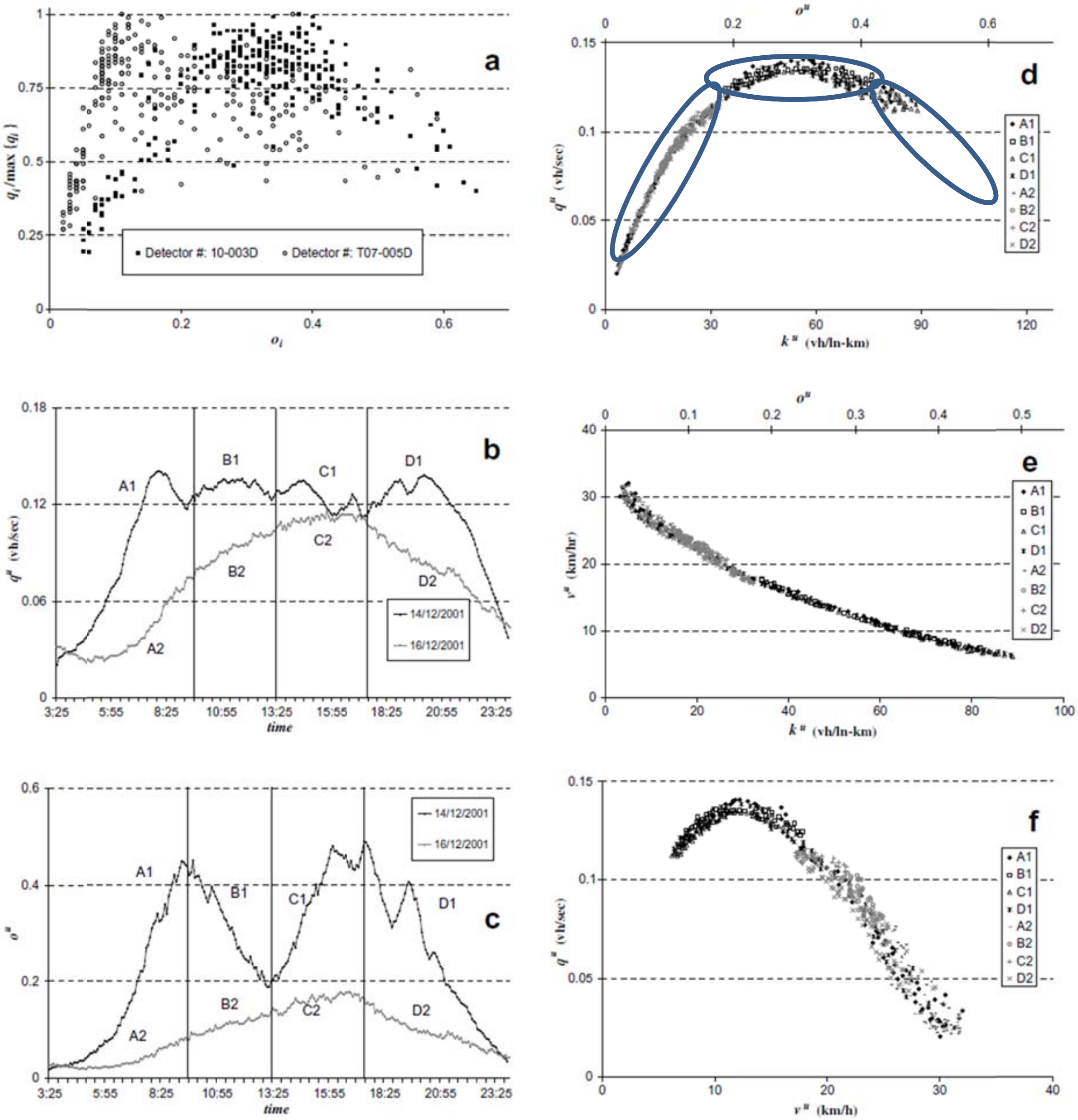

Figure 1 Loop detector data: (a) flow vs. occupancy pairs for two single detectors across a day; (b) time-series of average flow; (c) time-series of average occupancy; (d) average flow vs. average occupancy from all the detectors across two different days; (e) average speed vs. average occupancy; and (f) average flow vs. average speed.

By utilizing the MFD concept we can also show that the traditional average cost vs. demand curve (applied in most of the marginal-cost models) does not provide an accurate representation of congestion dynamics. Consider a region of a city, which traffic state is described by properties in the first paragraph of this section. Then the state of the system, n(t), is governed by the mass conservation equation (Daganzo, 2007):

$$\frac{dn}{dt} = I'(t) - o\big(n(t)\big) \tag{1}$$

where $\boldsymbol{n}$ is the accumulation (number of the vehicles in the system), $\boldsymbol{I'}(\boldsymbol{t})$ is the input rate (inflow) to the system at time $\boldsymbol{t}$, and $\boldsymbol{o}$ is the total outflow from the system as a function of accumulation. This equation simply explains that traffic systems are dynamic and to estimate the state of the system at time $\boldsymbol{t}$, the knowledge of the input flow is not sufficient, but boundary conditions are needed, i.e. the state of the system at a prior time $\boldsymbol{t'}$. Thus, a traffic model that estimates the average travel time based on a specific demand-cost curve ignores not only variations in the demand, but more importantly that this travel time will be different if the initial state of the system is in different congestion regimes.

To further explore this issue we present some additional results of data analysis from the Yokohama experiment by Geroliminis and Levinson (2009). For a whole day the total input flow entering downtown was calculated every 5min, as well as the total circulating flow inside the region and the average speed. The results for different times of a day are plotted and shown in Figure 2. Pairs of total flow vs. pace (1/speed) rely in a well-defined curve (Figure 2b), which is not affected by the different origin-destination pairs and demand variations across a day, i.e. it can describe a dynamic traffic system. Nevertheless, the input flow vs. pace curve (Figure 2a) not only has significantly more scatter, but also successive points follow different paths during the onset and offset of congestion in the morning and evening peak.

Thus, it might be more appropriate to describe congestion dynamics and derive efficient pricing policies by using the tool of the MFD.

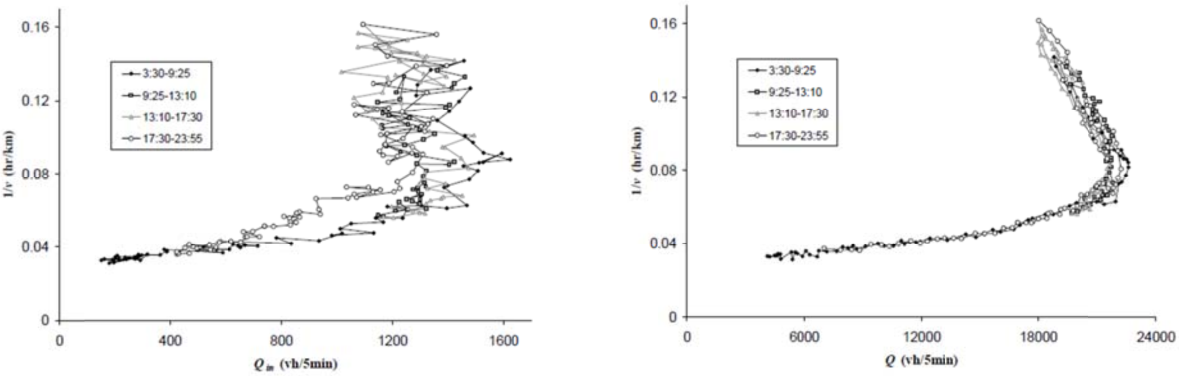

Figure 2 Loop detector data from Yokohama: (a) Input flow vs. average pace (1/speed) pairs across a day; (b) Total circulating flow vs. average pace pairs for the same day (Data resolution is 15min)

3. MATSim Multi-agent Traffic Simulator

We now introduce the basic concepts of an agent-based traffic simulation model. In this paper we will investigate the existence of the MFD in MATSim, a multi-agent based traffic simulation model. From a transport modelling perspective, multi-agent simulation is a method to integrate activity based demand generation with dynamic traffic assignment. Activity-based demand generation (ABDG) models generate a sequential list of activities and trips connecting these activities for every "agent" in the network. Demand generation is embedded in a concept of daily activity demand from which the need for transport is derived. Random utility theory is used to generate daily activity plans. Also there is a rule-based demand generation approach, which is based on psychological decision rules observed in stated-adaptation or other types of surveys. Each agent is assigned with his own utility function, therefore behavioural differences among the agents are realized. Besides, in the context of ABDG, the entire activity plan (mode choice, departure time choice and the activity sequence) is the unit of decision for an agent-based approach to iterate route assignments. These are superior to traditional demand generation model where all travelling agents have the same utility function towards cost and demand generation is not integrated with traffic assignment. MATSim has been widely applied for transport and land use studies (e.g. Axhausen (2008), Löchl and Axhausen (2010)) and travel behaviour modelling (e.g. Waraich et al. (2009), Vrtic et al. (2010),). The simulation structure of the system is depicted in Figure 3, and can be summarized as follows (more details please refer to Meister et al., 2010).

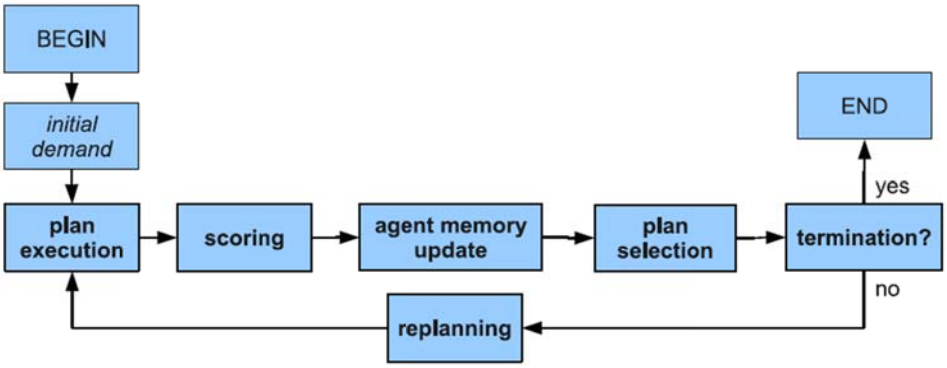

Figure 3 the structure of the MATSim simulation system

Initial demand. For every agent, one initial activity plan is generated. Input data such as population and land use data, as well as network data are processed to generate this initial demand. Each agent usually has only one plan.

Plan execution. In this step, the selected activity plans are simulated along the timeline in the model representation of the physical world. Due to the relevancy to this study, in the following we explain in detail the implementations of car trips in MATSim. Each trip with the mode car will be executed in a traffic flow simulation. This simulation consists (i) of loading the agent on the network link at which the previous activity is located at a given departure time, (ii) of moving the agent along a given route through the network, where it might interact with other agents under way, and (iii) unloading the agent from the network at the link of the destination activity. Different from a variety of models for the simulation of car traffic with discrete entities, including car-following models and lane-changing models, the approximation of traffic in MATSim is fulfilled as the following: each road segment is modelled as a First In First Out waiting queue, with a minimum service time of the length of the road segment divided by the maximum travel speed. The maximum number of vehicles that a queue can discharge equals the road capacity, depending on the number of lanes etc. The capacity is thus a predetermined value, as opposed to models with flow dynamics where the actual maximum outflow is influenced by the number of accumulated vehicles (density) and their interactions. The only concept related to flow dynamics integrated into the queueing simulation is a shockwave between vehicles travelling backwards at constant speed in the case of traffic jam discharge, bringing in some notion of kinematic waves represented in their full scale in macroscopic traffic models. Trips with modes other than car can also be interpreted by the implementation but are not executed in the physical environment. The execution of such trips is reduced to "teleporting" the agent from the origin to the destination activity in exactly the planned time, which means that trips with a mode other than car do not generate any interaction in the physical world.

Scoring. In order to compare activity plans, they are evaluated with a measure of general utility, called score, including utilities for activities and penalties for undesired manners. The related scoring function describes the agent's preferences. The score of a daily activity plan U_{plan} is given by equation (2):

$$U_{plan} = \sum_{i=1}^{n} \left(U_{act,i} + U_{travel,i} + U_{wait,i} + U_{short,i} \right) \qquad (2)$$

with n being the number of activities, $U_{act,i}$ being the score performing activity i, $U_{travel,i}$ being the score of traveling to activity i, $U_{wait,i}$ being a penalty for waiting instead of performing activity i, and $U_{short,i}$ being a penalty for performing activity i for a too short duration. Summarizing the main parameters from each of the item mentioned in equation (2) are the following, (i) the marginal utility for performing an activity, waiting and travelling by car. (ii) the capacity restraint of activity locations. (iii) the penalty for performing an activity shorter than planned. (iv) the marginal utilities for travelling by modes other than car and the marginal utilities for monetary expenditures of all modes. (v) the average monetary expenditures per kilometre for motorized modes of transport and the constant average speed of the modes. (vi) the access and egress time per trip to/from the means of transportation. For more detailed information, please refer to Meister et al. (2010).

Agent memory update. The initial demand typically consists of one activity plan per agent. Every time an agent is selected for replanning, another plan is added to its memory. Due to memory constraints, the number of plans is limited and over time some plans must be thrown out of memory (e.g. worst score plans).

Plan selection. Each agent decides which plan to select from its memory for execution in the next iteration. It chooses from the following options: (i) Replanning: with a probability, the agent is chosen for replanning by a replanning module. (ii) Probabilistic selection: for agents not chosen by a replanning module, one existing plan is selected for execution according to a Logit-type function. The purpose is to re-evaluate existing strategies in order to make them comparable to new activity plans generated by re-planning modules and to re-score a plan, as the congestion/traffic situation might have changed since its last evaluation/scoring.

Termination. The iteration cycle is stopped after the properties of the system fulfil some stopping criterion. Conceptually, the system has to run until the agents cannot significantly improve the score of the executed plans that is when an agent-based stochastic user equilibrium is reached.

4. Methodology

4.1 Perspectives

Section 3 describes the main characteristics of MATSim. An interesting question is to investigate if collective behavior (as expressed by a Macroscopic Fundamental Diagram) exists for an agent-based simulator, which is not modeling in details microscopic characteristics of traffic, like car-following, queue dynamics etc. In this section, we explain how we investigate the outputs of MATSim at both a microscopic and a macroscopic level in order to see the traffic physics representation. Especially, we are interested in macroscopic level, as expressed by the MFD.

Let us have a closer examination on how travel production (Vehicle kilometres travelled (VKT)) changes with accumulation (the number of vehicle in the network). Observing Figure 1d, three traffic regimes can be classified. Regime I (VKT increases with accumulation) represents under-saturated states where queues are transient and the total number of vehicles served is smaller than the maximum possible. Regime II represents saturated states. The links are filled part way with permanent queues and demand equals capacity. There is a limit to accumulation corresponding to queues that fill the links. In this regime, travel production (VKT) is constant, but never larger than the quantity $L*g*s$, where L is the link length, g is the duration of green phase and s the saturation flow of the signal. Regime III, production decreasing with accumulation, corresponds to oversaturated states and long queues or spillbacks are observed in many links. These states cannot arise by increasing the input flow, but a restriction from downstream is necessary, for example if queues from downstream links block the departures during the green phase. Regime III consists of states where queues fill the links, vehicles are stopped or moving at saturation flows. Congestion would be unevenly distributed over the network if states of individual link in regimes I and III occurred simultaneously. This would create points beneath the curve. We check if the output of MATSim exhibits such relationships. Especially we are interested in examining the existence of states in Regime III, where severe traffic congestion occurs.

The MFD resembles the classical Microscopic Fundamental Diagram (μFD). It has been observed from empirically derived μFD that the same flow can be achieved at two different speeds or densities. Possible explanations are two: (i) observing the lane flow upstream of a bottleneck gives the impression of a backward bending relationship: when demand is below the downstream active bottleneck's capacity, a flow on an upstream link can be achieved at high speed. When demand is above the downstream active bottleneck's capacity, the same flow on the upstream link can only be achieved at a low speed because of queueing. (ii) has to do with a capacity drop at the bottleneck itself under congested conditions. If traffic behaves as a queue through a bottleneck and generates spill-backs, traffic flow departing the queue may not stay at its maximum if (i) vehicles in the queue could not travel fast enough so that the front of the following car could not reach the point of the front of the leading car in the time allotted the service rate; (ii) if the departure flow is affected by external sources; or (iii) the bottleneck is not being fully served. Generally we want to examine if spill-back phenomenon can be observed in MATSim, since spill-back is consistent with the physics of traffic congestion and is the key reason of the existence of traffic production drop. Several µFDs will be drawn for some of the most congested links.

4.2 Data Derivation

For plotting a MFD, network traffic accumulation data and network traffic production data are needed. Traffic accumulation for a certain time interval t can be represented by space mean density of the whole network (vehicles per kilometer) K_t, which is a weighted number of vehicles remaining in the network, N_t, divided by the total length of the network L. See the equation below:

$$k_t = \frac{N_t}{L} = \frac{(\sum_I (k_i \cdot l_i \cdot n_i))}{(\sum_I (l_i \cdot n_i))} \qquad k_i = \frac{e_i - q_i}{l_i \cdot n_i} \tag{3}$$

where $i \in I$ denotes individual link i in the network. $q_i$is the number of vehicles leaving link i while e_i is the number of vehicles entering. k_i is the traffic density of link i, l_i is the length of link i. n_i is the number of lanes of link i. From MATSim output event file, this is calculated by the equation below, where $AELE$ stands for Agent Enter Link Event (the number agents entering a link in a certain time interval), $ALLE$ for Agent Leave Link Event, LL for Link Length and NOL for Number Of Lanes:

$$k_t = \frac{(\sum_I (AELE_i - ALLE_i))}{(\sum_I (LL_i \cdot NOL_i))} \tag{4}$$

Traffic production of a certain time interval t can be represented by the space mean flows of vehicles leaving each link i for the whole network Q_t, or by the number of arrivals a_i reaching destination at each link i for the whole network A_t. Given by the equation below:

$$Q_t = \frac{(\sum_I (q_i \cdot l_i \cdot n_i))}{(\sum_I (l_i \cdot n_i))} \qquad A_t = \sum_I a_i \tag{5}$$

From MATSim output file, this is calculated by the equation below, in which AAE stands for Agent Arrival Event:

$$Q_t = \frac{(\sum_I ALLE_i)}{(\sum_I (LL_i \cdot NOL_i))} \qquad A_t = \sum_I AAE_i \tag{6}$$

The basic temporal resolution is one-minute. This means the number of $AELE$ and of $ALLE$ are counted every one minute. If, for example, talking about a five-minute aggregation, for each interval t, k_i is calculated as the average value of the five corresponding one-minute values, given by the equation below: $k_i = \frac{\left(\sum_i^{i+5} k_i\right)}{5}$.

4.3 Network Filtering

One of the main characteristics of congestion for a well-defined MFD is that the target network is homogeneously loaded (congestion is not very unevenly distributed). We try to identify a high demand sub-network, so that we can test the existence of an MFD. We develop a filter to find a network with these features. To do this, we first calculate density of every individual link of a network, which is centered at 2km south to the main train station of Zurich and has a radius of 15 kilometers. Bubble plots of these densities are shown in Figure 4 for morning peak and in for evening peak. The x and y axis values (meters) of the center of a bubble indicate the coordinate of the center of a link. The radius of a bubble indicates the value of the link's traffic density. One can see from these two bubble plots for different times of day (morning and evening), the most congested part is around the chosen center. For this scenario, the target area then is a 4.5km-radius network, centered in the geographical center of city Zurich, containing 909 links including arterial roads, connector roads and some access roads.

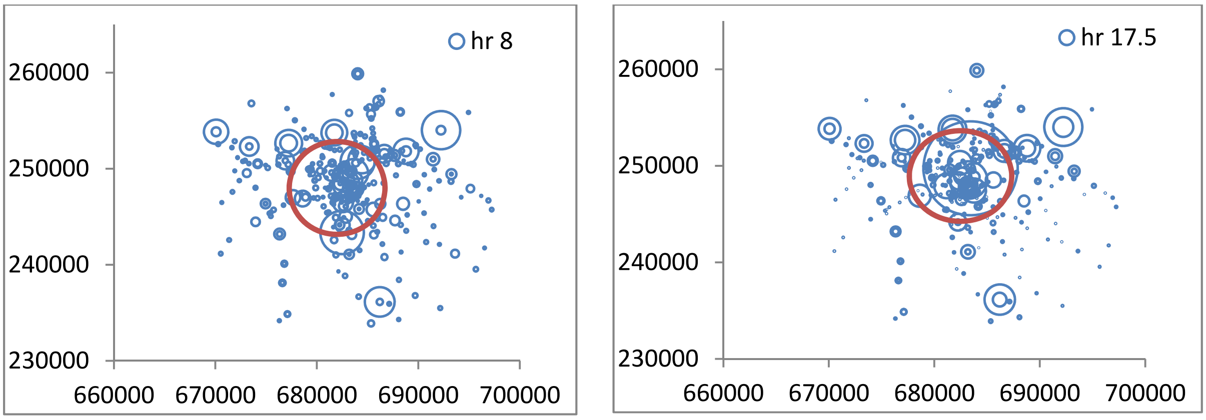

Figure 4 Bubble plot of traffic density at (a) hour 8am and (b) 17:30pm

4.4 Analysis

We now investigate the following properties of the simulation results of MATSim: (i) check the existence of the MFD and (ii) look at the rationale of resulting FDs. Furthermore, due to the heterogeneity nature of traffic the MFD sometimes has irregular scatters or hysteresis loops. This is showed in recent studies by Mazloumian et al. (2010), and by Geroliminis and Sun (2010). We will provide an explanation if, how and why heterogeneity occurs in the Zurich simulation of MATSim.

5. Results

In this section, we present some results from three simulation scenarios of MATSim. In Scenario 1 (Mohit, 2010), agents equivalent to 10% of the real traffic demand are employed over a network containing urban arterial roads, distributors and some access roads. While in Scenario 2 and 3, agents equivalent to 25% of the real traffic demand are employed over a navigational network in which all the links of the studied area Zurich are included (Meister et al., 2010, did for the whole of Switzerland). Comparing to Scenario 1, more agents are sent into the network therefore more traffic are generated in Scenario 2 and 3. Comparing Scenario 3 to Scenario 2, flow/capacity ratio is lowered in order to manually create congestions.

5.1 FDs and Spill-back Effect

We first investigate if congestion effects and spill-backs propagate in the study network. Flow $\mathrm{q_i}$ and density $k_i$are calculated to construct the individual link i FDs for Scenario 1 In Figure 5, the FD for link "106728" is shown with blue dots. X-axis is "density" while y-axis is "flow rate". One can observe that at density around 5veh/km, the service rate reaches its maximum and remains the same value until density around 35veh/km. Then flow rate starts to decrease. This indicates severe congestion happens at the latter point. Secondly, one can observe the spill-back effect at the upstream of link "106728" shown with red dots. Clearly there is a reduction of flow rate on the upstream link given that they have the same link capacity. Thirdly, we further check the downstream link of "106728". The motivation is the following: If congestion of one link caused the drop of production rate and congestion on its upstream, for a series of consecutive links there should be one link downstream which operates just at its maximum, i.e. at capacity (active bottleneck). Link 106132 is downstream of link 106728. The FD is displayed in Figure 6, together with one link further downstream of Link 106132. As flow decrease is still evident on the right part of the FD curve, we repeat the same process. Shown in Figure 7, link 106310 shows a saturated condition while its downstream link operated at the free flow part of the FD curve. These observations make clear that queues are growing from downstream to upstream and blocking effects are present in the simulator. It is also clear that the individual fundamental diagrams exhibit high scatter, especially in the congested regime.

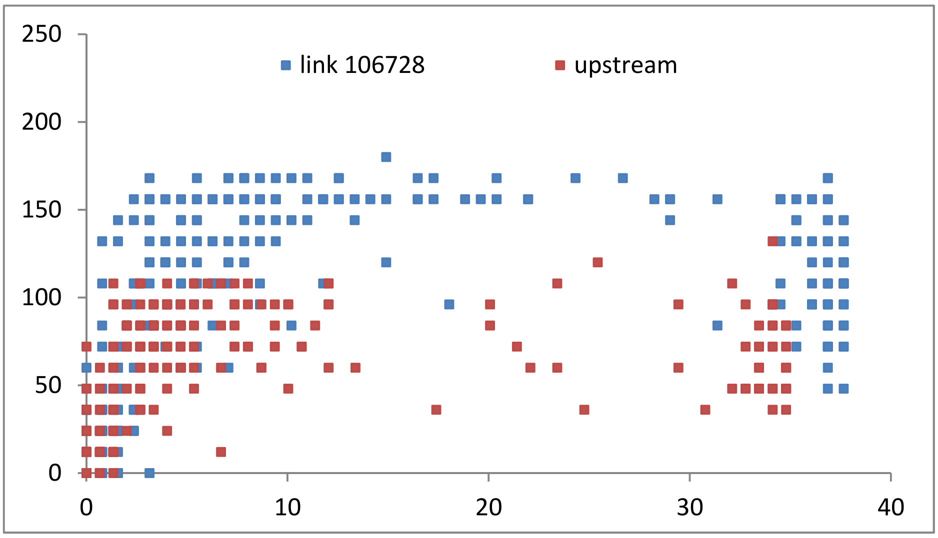

Figure 5 the Fundamental Diagram for link 106728 and its upstream link

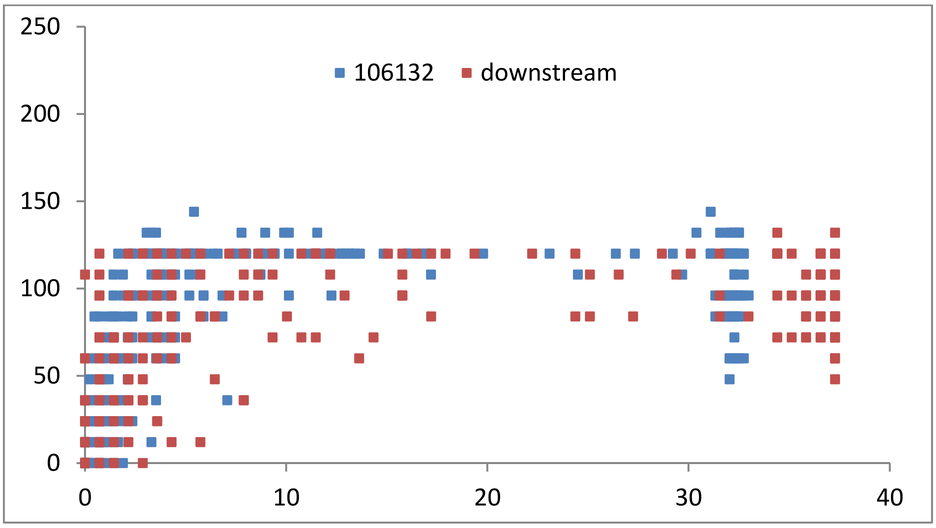

Figure 6 the Fundamental Diagram for downstream links of link 106728

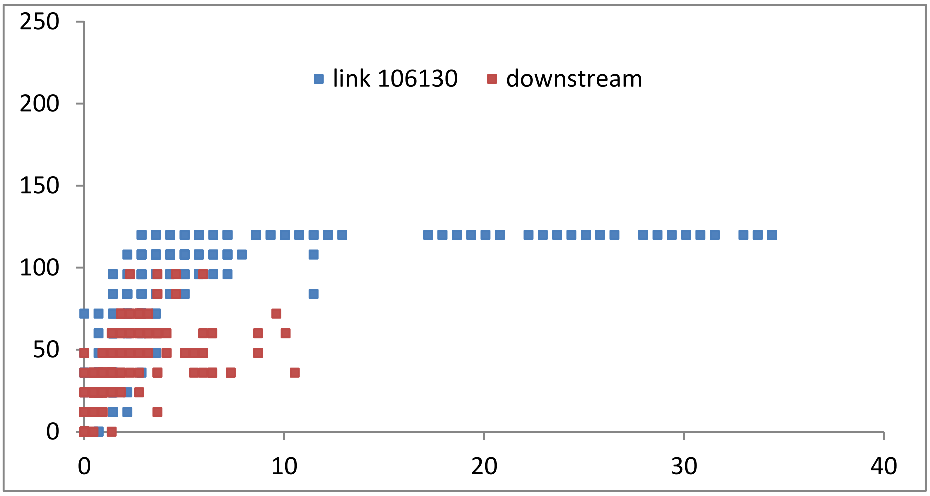

Figure 7 the Fundamental Diagram for link 106130 and its downstream link

5.2 The MFD

The MFD for a 4.5km-radius Zurich center of Scenario 1 is shown in Figure 8a. Compared to Figure 1d, one can see that the output from MATSim shows the existence of the left part of a MFD, showing that only Regime I and the beginning state of Regime II exist. This network on a macroscopic level is not heavily congested although on a microscopic level several links (including the ones in Section 0) experience long queues. Even if we further filter the network to a 1.5 kilometre area, as shown in Figure 8b, we get the same observation. To observe congested states and a complete MFD, we collect data from Scenario 2 and Scenario 3). In these scenarios, many more agents are employed for simulations and consequently more events (traffic) are generated. We show the MFDs of these scenarios in Figure 10 and Figure 11, plotting arrivals (the trip finish rate) against accumulation. One can observe that (i) comparing to Scenario 1, Scenario 2 and Scenario 3 have a complete Regime II in which network is operated at its capacity and (ii) congestion Regime III happens, as the number of vehicles in the network increases while the number of vehicles out of the network decreases.

Although the demand is not high enough to see a complete Regime III, we can see MATSim is capable of representing the traffic dynamics at a macroscopic level.

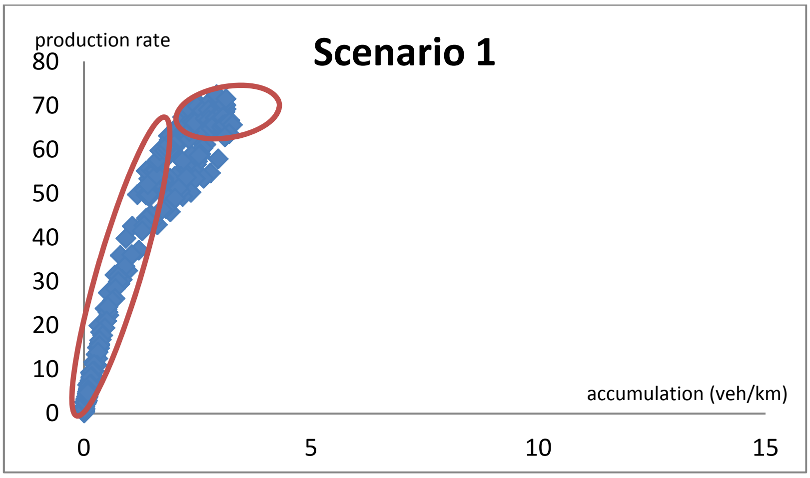

Figure 8a the MFD of the filtered network in Scenario 1 (radius-4.5km Zurich center 1)

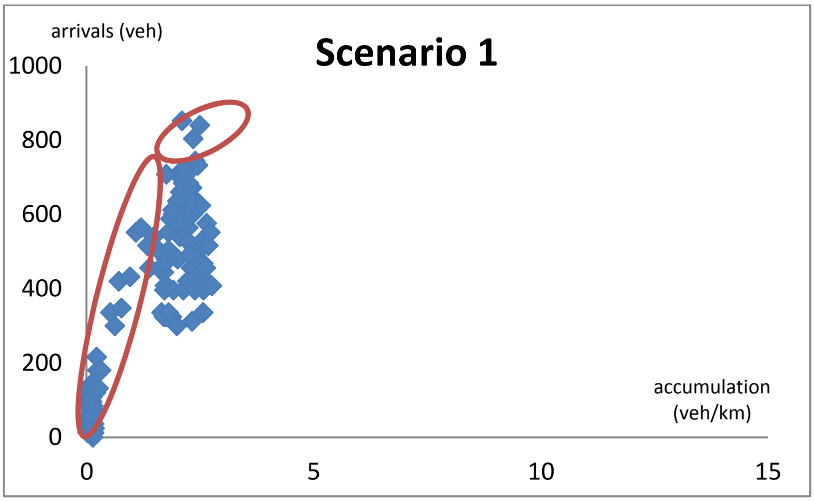

Figure 9b the MFD of the filtered network in Scenario 1 (radius-1.5km Zurich center 1)

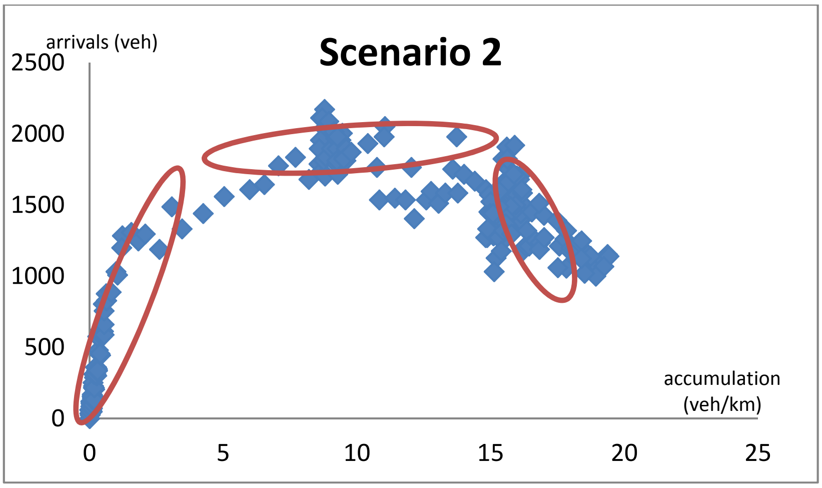

Figure 10 the MFD of the filtered network in Scenario 2 (radius-1.5km, Zurich center 2)

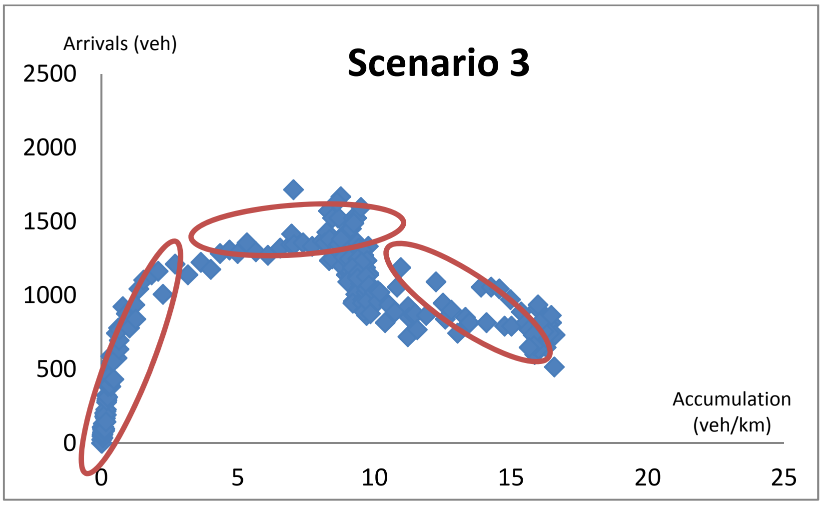

Figure 11 the MFD of the filtered network in Scenario 3 (radius-1km, Zurich center 3)

5.3 A Careful Look in Hysteresis Phenomena

Now let us have a more careful look to Scenario 1 for an interesting observation in the shape of the MFD. By zooming in the MFD in Figure 8, one can see loops formed after connecting scatters by time series in Figure 12. Similar phenomena have been observed by Geroliminis and Sun (2010) and defined as Hysteresis phenomena of a MFD: higher network flows are observed for the same average network density in the onset and lower in the offset of congestion. They argued that this is because there are different spatial distributions of congestion for the same level of average network density for different times of a day. We draw link density distributions of all links in the network at three different times, where the network holds the same amount of vehicles. The chosen times are 6h35 (the highest point), 9h15 (the lowest point) and 11h40 (medium point). They refer to the onset of the morning peak from 6h35 to 9h15, and the offset from 9h15 to 11h40. Density distribution representing the status of traffic is shown by bubbles in Figure 13. Traffic is more uniformly distributed at 6h35 than at 11h40, while at 9h15 densities are extremely high at some locations. Besides, we find that at 6h35 only 30 links have densities more than a pre-defined value 10 (about 100vh/km/lane), while at 9h15 there are more than 70 links. These findings prove that the hysteresis is caused by uneven distribution of congestion, which is consistent with previous studies of real data.

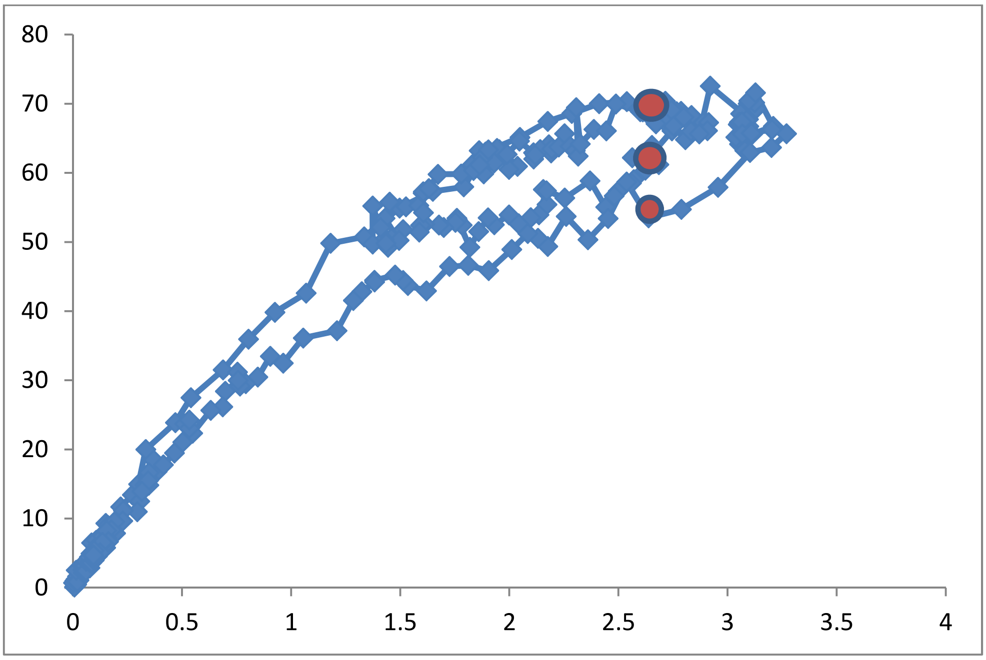

Figure 12 observed hysteresis of the MFD by zooming in Figure 8

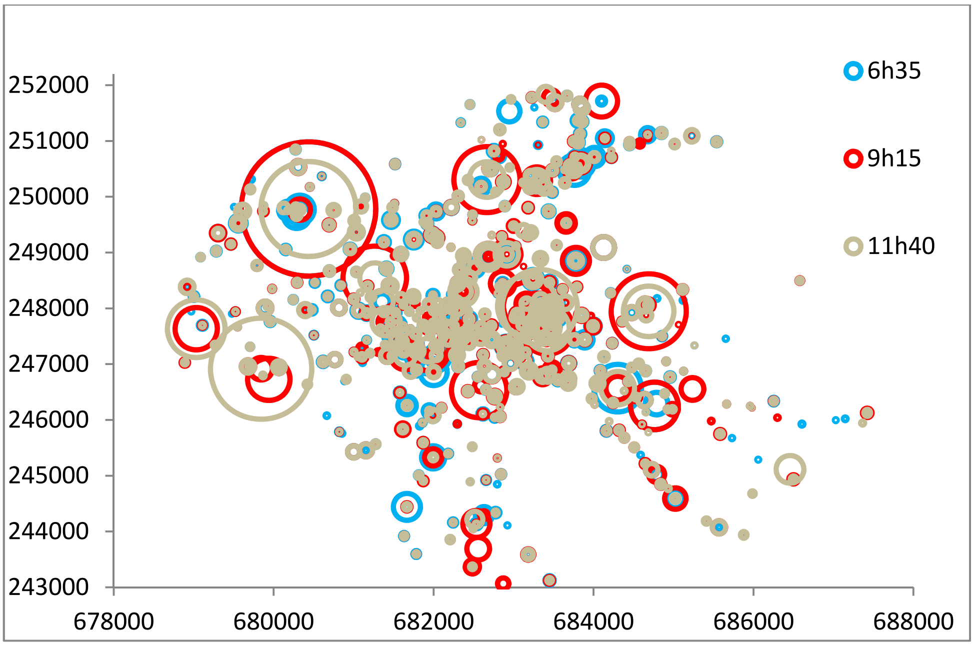

Figure 13 density distribution of the network at time 6h35, 9h15 and 11h40.
Axis represent coordinates of links (x,y-axis represent coordinates)

6. Conclusions and Future Work

In this paper we explore the existence of a Macroscopic Fundamental Diagram model with agent-based traffic models. These findings are a preliminary step for later investigation on area- and cordon- pricing schemes. We first describe the important features of the MFD model and introduce the key concepts of a multi agent-based traffic simulation model

MATSim. We then explain how we test if the outputs of MATSim represent traffic flow dynamic as expressed by FDs and MFDs.

Our initial results are interesting and promising. By examining the outputs of three MATSim simulation scenarios, we would conclude that the productions of MATSim are consistent with the physics of traffic. On microscopic level, MATSim is able to reflect spill-back effect once congestion is formed. This is observed on consecutive congested links. While on macroscopic level, MATSim shows an MFD between network production rate or network trip finish rate and network accumulation. In addition, the cause of hysteresis in the MFD can be explained by its own output which is the uneven distribution of congestion. All the findings mentioned are consistent with previous studies with simulation data or real life experiment. We would also conclude that combining the MFD model and the agent-based model MATSim has indeed great potentiality for studying congestion pricing, as optimal tolls can be developed, based on demand elasticity and traffic supply dynamics.

In an earlier research of Geroliminis and Levinson (2009), a macroscopic congestion pricing model is proposed to determine an optimal toll on road network. Using an extended Vickrey model as a cordon-based toll scheme and an MFD to describe traffic network dynamic, the proposed scheme is proved Pareto-efficient. However, what the model did not deal with is elastic demand and heterogeneous population. As we know in reality, travellers have different utility functions towards travel cost and schedule delays, they choose when to start their trips and whether do their trips, they face choices of known routes and they face choices of available transport modes. In these senses, it seems microscopic models, such as agent-based frameworks with heterogeneous individual travellers collectively creating congestion, if fulfilled a MFD property, can generate more realistic travel behaviours and optimal tolls. With the available use of MATSim, which is a multi-agent based traffic simulator, this idea can be tested.

Following this study, we propose to take the following steps: (i) investigate other simulation scenarios, in which higher demand is employed in order to see if there is a complete MFD. However it is desirable that the optimal toll ultimately will keep traffic operate in Regime II and not Regime III. (ii) Investigate how congestion pricing schemes work in MATSim and be controlled by the MFD. (iii) Investigate how different congestion pricing schemes can improve mobility patterns. (iv) Address equity issues in congestion pricing.

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