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Exploring Effects of Network Spatial Characteristics on
Macroscopic Fundamental Diagram

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Abstract

Macroscopic Fundamental Diagram (MFD) builds a relationship between the outflow and accumulation of the network in variant of demands and appears frequently in urban transportation networks under certain conditions. However, MFD is not expected if the network is heterogeneous. This paper studies the impact of network spatial characteristics on the existence and characteristics of a MFD based on simulation. Firstly, the paper analysis the network spatial influence factors, including the size and the critical link of the neighborhood that may influence the existence of a MFD and its shape respectively. Then, how this factors influences the property of MFD is explored.

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1 Introduction

Recently, Daganzo and Geroliminis (2008) proposed a new concept of macroscopic relationship between average network flow and density, which is called the Macroscopic Fundamental Diagram (MFD). Besides, they also explore the way to get it (Geroliminis & Daganzo, 2007, 2008), (Daganzo, 2007), (Courbon & Leclercq, 2011).

They made a field experiment in Yokohama (Japan) and reveal that a macroscopic fundamental diagram linking space-mean flow, density and speed exists on a large urban area. The experiment used a combination of fixed detectors and floating vehicle probes as sensors. About 500 fixed detectors that offer vehicle accounts and

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occupancy measurements and 140 taxis are used in the experiment. When they analysis the data just like Thomson (1967) analysis the data from the central London, they found that when the somewhat chaotic scatter-plots of speed vs density from individual fixed detectors were aggregated, the scatter nearly disappeared and points grouped neatly along a smoothly declining curve, which suggests that an MFD exists for the complete network.

Since the Macroscopic Fundamental Diagram was proposed, a lot researches have been done to reveal what kinds of network have the MFD. At last, they found that the network which is homogeneous will have a well-defined MFD (Daganzo, 2007). In other words, the network that the congestion is even and consistent distribution will get the MFD with a low scatter.

However, sometimes it’s hard to satisfy this condition, especially in big cities. It’s difficult to make sure that the whole network is neither congest or uncongested simultaneously. Therefore, if there is a well-defined MFD exist when the congestion in the network is uneven and inconsistently distributed? If not, what and will it influence a well-defined MFD.

Several works have been done in order to answer these questions. Buisson and Ladier (2009) use all the data available for a medium-size French city to explore the impact of heterogeneity on the existence of a MFD. They studied the impact of differences between the surface and highway network, distance between loop detectors and traffic signals within the surface network, differences between penetrating and ring roads within the highway network. But in the paper they don’t explore the how the traffic signal(e.g. cycle length) affect the shape of the MFD, what’s more they didn’t use the flow and the occupancy to study this different, they didn’t reveal the relationship between accumulation of the vehicles in the whole network and the outflows in the network.

Geroliminis and Sun (2011) explore the hysteresis phenomena of a MFD in the freeway network systems. By analyzing real data of Minnesota’s freeways, they show that different freeway sub-networks do not have a well-defined MFD with low scatter because the aggregated patterns do not just exhibit some high degree of random scatter. They also show that freeway network systems exhibit consistent hysteresis phenomena in a MFD plane, where higher network flows are observed for the same average network density in the onset and lower in the offset of congestion. But the paper doesn’t explore how the variations in the structure of the network affect the shape, the scatter and the existence of an MFD. Gayah and Daganzo (2010) studied the effect of turning volume on MFD with the help of simulation. They found that different ratio of turning volume will influence the MFD. Ji and Geroliminis (2010) also explore the Spatial and Temporal of Congestion in urban networks.

Although some features of MFD have been studied, the impact of network spatial characteristics on the existence and characteristics of a MFD is still not clear. In other words, how the size of the neighborhood and the critical link in the neighborhood will influence the shape and scatter of MFD are still unclear. To this end, we use the connection between the accumulation of the vehicles in the whole network and the outflow of the network to investigate the impacts of these influence factors and lay the foundation of dividing the whole network and using the MFD predicting the traffic condition. Instead of using virtual network and the virtual data, we will use a realistic network which is a part of the whole network of Beijing, and field data including traffic volume, signal plans of it.

This paper is organized as follows: the next section presents the basic information of the network and data used in this study and proves the existence of MFD in the network. The analysis methods are also given in this section. Section 3 analyses the influences of various factors on the MFD. Conclusions and discussion are given at the end of the paper.

2 The MFD of Beijing network and the analysis method

Our study area is in the west of Beijing, which is about 9km². The area is consisted of 5 arterial roads and large numbers of minor roads. The main roads are connected by viaduct and most of the secondary roads are connected by signal intersections except some are unsignalized intersections. Generally speaking, the network is well-
designed. The main road has 6 lands and the land of secondary road is range from 2 to 4. There are 37 intersections in the studied network, which contain about 21 signalized intersections with the cycle length range from 65 to 118 seconds. The network will get into congestion during the peak hours. We can see our study area from Fig.1.

VISSIM is used to build a simulation model of the studied network. VISSIM is a popular microscopic simulation software, which is developed by PTV, Germany. It’s very easy for us to get important information (e.g. volume, speed and density) after we set up the network. In this paper we will explore the connection between the accumulation of the whole network and the outflow (the vehicle which run out of the network), so volume is the key parameter for us and it’s possible for us to research with the help of VISSIM. According to our study area in the digital map (see the left picture of Fig.1), we set up the simulation model in VISSIM (see the right picture of Fig.1).

An important aspect of the traffic model is how each vehicle’s route choice is determined. The traffic demand can be entered in two ways: 1) as fixed traffic counts and turn movements at intersections or 2) as a time independent OD table. If the demand data is entered as trip generation and turn percents, then vehicles chose their routes implicitly by making turns in the prescribed proportions at each intersection. When traffic demand is entered via an OD table VISSIM estimates a static equilibrium distribution of traffic on the network consistent with the demand and generates equivalent traffic generation and turn movements to recreate this distribution (PTV, 2007). We choose the second way because if conditions on the network change, the same trips can be served by routing vehicles differently on the network.

2.1 Existence of MFD in our network

Before starting to explore the effects of MFD, it is very import for us to confirm a well-defined MFD exist in our study area D. The performance of the network is simulated with peak hour data. The input and output vehicle are recorded every 60 seconds. Then we can get the number of cars run out of the network O(outflow), which is the sum of the measures at individual links and the A(accumulation) in the net every minute. The two important parameters can be expressed:

\[
O = \sum O_i \tag{1}
\]

\[
A = \sum I_i - O = \sum I_i - \sum O_i \tag{2}
\]

Where \(O_i\) is the outflow of every link \(i\) every 60 seconds and we can get the data from the detector; \(I_i\) is the input of each link \(i\) and we can also get it from the detector.
According to the data from the detectors every minute, we get the MFD of our study network, which is shown in the Fig. 2, 3 and 4.

**Figure 2: The MFD of our study area**

![MFD of the study area](image1)

**Figure 3: The outflow changes with time**

![Outflow changes with time](image2)

**Figure 4: The input changes with time**

![Input changes with time](image3)

In order to get the reliable results and smooth the stochastic variations, we simulate the network five times. Fig.2 shows that the software works very stable and how travel outflow changes with accumulation. The three different parts are clearly noticeable, pare 1 (the yellow line) is the beginning of vehicles run into the network, with the increase of vehicle in the net, the outflow is increasing; when more and more vehicles run into the network most links are operating at capacity, and the outflow will not go up continuously with the increasing of input and this is the part 2 (the blue line); we can see from the part 3 (the black line) that the outflow will decrease
if the accumulation keep increasing without any control actions. Fig.3 and 4 show the change of input and outflow volume with the time. From Fig.3 we can see that the output volume will increase at the beginning, and then keeping at the 450veh for a period of time, finally it goes down gradually. It’s easy to understand this phenomenon that at first, there is no car in the network, so the output will increase with car running into the network rapidly. When most of the links in the network operating at capacity, the outflow comes to the maximum. However, with the accumulation going up, the outflow will decrease. It’s obvious that the network is in gridlock and it’s hard for car to run out of the net. We can see from Fig.4 that the vehicles gets into the network, decreases from the beginning to the end, this is because the accumulation in the network keeps increasing which makes it become harder and harder for vehicle to run into the network. From the result, we can make a conclusion that that although the whole network is not satisfied the homogeneous condition (the network contains different kinds of roads with different congestion levels), the scatter is accessible, we can also say that the network has a well-defined MFD. Therefore, we can explore the Influence factors in the network during the next section.

2.2 The analysis methods

Through the analysis above, we know that if the congestion is even and consistent distribution in a network, then the network has a well-defined MFD. Is there any different between different networks? If there is, what’s the reason?

In order to know whether there is are different between different networks, and the reasons for these difference. In next section, we will explore the impacts of network spatial influence factors, including the size and the critical link, to reveal how this factors influence the MFD.

To have a systematic investigation of the influence of these two factors, this study has employed the following analysis procedure:

To analysis how the size of the network influence MFD, we will change the number of intersection gradually in the network to see how the MFD of the network change. At beginning, the network has one intersection. When we expand the network we keep the volume of the link in the network the same. In order to eliminate the influence of different traffic situation we choose two cases, case 1 is in gridlock while case 2 is not. Finally, six study areas are showed in Fig.5, denote D1, D2, D3, D4, D5, and D6. Case 1 is consisted of D1, D2, and D3 while case 2 is consisted of D4, D5, and D6.
The intersection in study area D1, D2, D3 are uncongested, while the intersection in D4, D5, and D6 is located on the main road and always get into congestion.

We define the link whose traffic condition is very different others in the neighborhood the critical link. To analysis how the critical link in the network influence MFD, we choose two study areas to make a comparative analysis. One of the study areas is D3 in Fig.5(c), the other one is D7 in Fig.6.

Comparing with D3 and D7, we can see that D7 has a congested link and two congested intersections than D3. The size doesn’t change too much, but the traffic volume in the link is very different from others and we call it is a critical link. From this comparing, we can see the critical link has a great influence on MFD. Then, to see how the critical link influences the MFD, we change the volume in the link to meet with other links in the area. Two ways are used to change the volume in the critical link, the control method 1 is to reduce the volume while the saturation is not change (e.g. we close some lanes) and the control method 2 is to reduce the volume and saturation together (e.g. change the OD to reduce the demand in the link). From the result we can not only understand how critical link influence the MFD, but how saturation influence the MFD further.

To identify how the size and critical link jointly influence the MFD, we analysis the study areas D, D3, D7. From the result of each area we know the answer.

A detailed analysis will be shown in the next section.

3 Analysis the effects of MFD

3.1 The influence of the size of neighborhood

To know how the factor of size influences the MFD, we get the input and output flow from the detectors to deduce the relation between accumulation and outflow of each study area. We get the data from the same time simulation, the relation for D1,D2,D3,D4,D5,D6 are revealed in figure 8 from (a) to (f) respectively.
Firstly, compare the MFD of D and D3. From Fig. 8(c) and Fig. 2, we can see that except the value of axis, the variation tendency of the MFD is almost the same and the scatter of MFD is accessible. In the network D, when the accumulation is 4000veh, the outflow comes to the maximum value 450veh, while in the D1, this value is (500,120). The main reason is that these two networks have different numbers of links and intersections, which make they can contain different numbers of car.

We define that if the change of influence factor has no effect on the shape and scatter of MFD, we say this factor has no effect on MFD. According to this definition, we may say that in the case of D and D1, the factor of size has no effect on MFD. But compare with Fig. 2, Fig.8 (c) and Fig. 8(a) (b), we find that if the area has few intersections and roads, we are hardly to get the relation between accumulation and outflow. But when the area is “big” enough then we may get a well-defined MFD (we can see the case D and D3). Then we can make the conclusions that if the network is big enough, the size will have no effect on the shape and scatter of MFD. Otherwise, the network will not get a well-defined MFD.

We also prove it with case 2. From Fig. 8(d)(e)(f), we can see that with the increasing of the number of intersections in the study area, the relation between outflow and accumulation become more and more clearness. From Fig. 8(f) we can also see this variation tendency.

3.2 The influence of the critical link of neighborhood

To investigate how critical link influences the MFD, we get the relation between accumulation and outflow of D7 and the result of after taking traffic control. The results are as follows:
Comparing Figure 8 (c) and Fig. 9 (a), we can see that the scatter in Fig. 9 (a) is so big that it’s hard to find the relation of outflow and accumulation. Which mean that the critical link really has an influence on MFD.

The yellow line in Fig. 9 (b) represent the variation tendency of the MFD of D7, it’s the result before we take any actions to change the volume in the critical link. While the green one is the tendency after we take the control method 1 and the blue one is for control method 2.

As for the scatter, we can see that after we take actions to reduce the volume on the main road to match others in the area, the scatter is better than nothing is done. Moreover, the variation tendency of the green line and blue line are the same except that the scatter of action 2 is smaller than action 1. Generally speaking, the saturation almost has no influence on MFD, it is the traffic flow in the critical link that influence the MFD.

We can also see from the lines that when the accumulation is low, the outflow of the study area is higher if we do nothing. But when the accumulation is high (about 400 in the Fig. 9 (b)), the outflow of study area is higher if we take some measures to control the volume on the main road.

Then we can make a conclusion that the critical path has different influence on MFD according to the accumulation in the neighborhood.

Besides this finding also conforms to reality. In practice, we’ll not take any actions to control the volume on the main road if the flow is low and the vehicle can run safety, so after taking actions to reduce the volume on the main road, the outflow reduces. We can see the lines from Fig. 9 (b), when the accumulation is less than 400 that the green and blue lines under the yellow one. On the contrary, when the flow on the main is high we will take some control measures to improve the capacity. We can also see that when the accumulation is more than 400, the yellow one under the green and blue lines.

From Fig. 2 we find that although the study area D has many critical paths, it still has a good MFD. The reason for this phenomenon is that during the simulation, some critical path working in capacity while others are not. So the influence of these two situations offset. Then the whole network has a good MFD.

3.3 Factors jointly influences

According to the analysis above, now we know that the size of the network and the critical link in the network will influence the MFD of the network respectively. However, according to the definition of critical link it’s easy to find that these two factors are always working together. If we include/exclude some critical path when we divide the network, the size of the network will change together. So in practice, they will influence the MFD together. From Fig. 2, Fig. 5(c) and Fig. 8(c) we find that the size of D7 is bigger than D3 but don’t have a well-defined MFD because of the influence of critical link; while D has a lot of critical links, it also has a well-defined MFD. This is the result of the influence of size and critical path together.
There is no doubt that if the network is homogeneous, it has a well-defined MFD [1]. Some experiments also tell us that sometimes even if the network is not homogeneous, it also has a well-defined MFD and this is the result of the jointly influence by many factors. In this paper we find a pair of factors which are the size and the critical path.

Above all, if the traffic is even distributed and the size is big enough, the size of the network will not influence the scatter of MFD. However, if the size of neighborhood is too small, the MFD of the neighborhood will still influenced by size; if the congestion is uneven and inconsistent distributed, and the network includes some critical path, it will be hard to get a well-defined MFD unless the neighborhood is big enough to reduce the influence caused by the critical path. That is, it is the critical path and size that influence the scatter of MFD together. So it’s very important to find out what kinds of links are the critical paths in practice. Using the same way to research other roads, we find that the road which is easy to get in gridlock has a great effect on the scatter of MFD. So in practice we should take actions to prevent the road get into gridlock.

4 Conclusions

The results in this paper show that the Beijing network has a well-defined MFD between network accumulation and outflow. The data from reality prove that it is possible to put MFD into use in Beijing. On the basis of this characteristic, we explore the effects of network spatial characteristics on macroscopic fundamental diagram networks. We can see from the result that the critical link has a great effect on the shape of MFD. Moreover, sometimes the size of the network will not influence the shape of MFD, but sometimes the size will influence the shape of MFD.

Moreover, the findings are also important for us when we divide the whole study network into several traffic neighbourhoods. If the network is heterogeneity, we can control the size of the neighborhood and the critical links in it to get a well-defined MFD. So the next work is to explore the way to divide the network with the analysis above.

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