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Research Article

Dynamic Analyses of Urban Expressway Network with Mesoscopic Traffic Flow Model Integrated Variable Speed Limits

Shu-Bin Li,[1] Bai-Bai Fu,[2] and Wen-Xiu Dang[1]

[1] *Public Security Department, Shandong Police College, Jinan, Shandong 250014, China*
[2] *School of Architecture and Urban Planning, Shandong Jianzhu University, Jinan, Shandong 250101, China*

Correspondence should be addressed to Shu-Bin Li; li_shu_bin@163.com

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Urban congestion is a major and costly problem in many cities both in China and other countries. The purpose of building urban expressway is to alleviate the growing traffic pressure. In this paper, the mesoscopic traffic flow models are improved by variable speed limits strategy for the dynamic of vehicles on urban expressway network. The models include static queuing model, the velocity model, and the movement model of the vehicle. Moreover the method of the simulation is also proposed. So that we can get the corresponding variable speed limits values and aid traffic managers in making decisions to develop a network traffic flow control strategy. In the end, the elevated expressway of Jinan city is used as a simulation example. We investigated the performance of the transport system with averaged density, speed, and flow on link. We also analysed the dynamic of the traffic system on expressway network at different demand levels. The simulation results show that the models are feasible and effective and the variable speed limits strategy can successfully alleviate the traffic congestion in some extent. The operational efficiency of the transportation system is greatly improved.

1. Introduction

The problem of traffic congestion has become more and more serious in the cities around the world; in particular, it is one of the most important issue in big cities. Growing traffic congestion has seriously hampered the economic development and brings inconvenience and damage to people's work and life. Intelligent transportation system (ITS) is an effective way to solve the above problem, and the dynamic traffic assignment (DTA) is the key technology. The objective of DTA models is one of the most important foundations of intelligent transportation system. It is also the theoretical basis of Advanced Traffic Information System, Advanced Traffic Management System, and Super Smart Vehicle System. It is a forward-positioned research work in traffic and transportation field and has received increasing attention in recent years.

DTA has two steps, one is traffic flow model which descript the dynamic of vehicles on the network, and the second is a dynamic network loading. Typically, the traffic flow models are divided into macro-, micro-, and mesoscopic model. The levels of detail in these models range from microscopic to mesoscopic to macroscopic. Macroscopic models depict the traffic at high levels of aggregation in flow, speed, and density without having to explicitly represent vehicles. On the other hand, microscopic models are aimed at describing detailed information about an individual driver's adjustment of speed or lane position in reaction to other lead or adjacent vehicles or roadway conditions. Generally, the mesoscopic simulation models maintain varying degrees of characteristics associated with both macroscopic and/or microscopic model; the mesoscopic traffic flow model is a cross-model between the macro and micro, and the model in the practical application can ensure both accuracy and computational efficiency.

However, the mesoscopic traffic flow model is not clearly defined so far; paper [1] defined that all the excepted models of the macroscopic and microscopic traffic flow models are referred to as mesoscopic traffic flow model. A large number of simulation software such as DynaMIT [1], DynaSMART-X [2], the German company PTV Visum-online [3], and Taiwan

Institute of Transport Studies support DynaTAIWAN [4] are all based on simulation-based dynamic traffic assignment techniques; the core theoretical model is mesoscopic traffic flow model.

In the literature, several recent mesoscopic models have been developed. The gas-kinetic continuum model, first published by Prigogine and Herman, employs the Phase-Space Density (PSD) as its core mechanism [5]. Another model class is the simulation-oriented models that are aimed at describing vehicle trajectories following link, segment, or cell structure of the network arcs at every simulation clock tick [1]. Some recent studies [6, 7] categorized dynamic disaggregate mesoscopic network loading problems based on whether vehicles are either grouped into discrete packets or spread within continuous packets.

However, these are not considered variable speed limit (VSL) factors. Lin et al. [8] presents two VSL algorithms for traffic improvement, which did combine with RM. The author believes that VSL not only can improve safety and emissions but also can improve traffic performance by increasing throughput and reducing time delay. Hegyi et al. [9] used a VSL strategy to suppress shock waves. A lot of studies have been implemented in real life, such as in Germany [10, 11]. Bertini et al. [10] used an empirical approach to investigate the effectiveness of reducing congestion at a recurrent bottleneck and to improve driver safety by using feedback to the driver with advisory variable message signs (VMS) on a highway stretch (18 km). Most of other applications are on the highway and motorway [12–14]. Some of them integrated ramp metering [14, 15]. By indexed, we have not found related research in the urban expressway.

In this paper, we propose the integration of mesoscopic traffic flow model via VSL and extend to urban expressway. The following is presented according to the following structure. Section 2 introduces the improved related traffic simulation models and analytical properties of anisotropic mesoscopic simulation modeling; Section 3 discusses the path generation algorithm; Section 4 presents simulation method and environment as well as a set of numerical results for urban expressway; Lastly, Section 5 offers concluding remarks and discusses further research ideas.

2. The Improved Mesoscopic Traffic Flow Model

2.1. Traffic Network Description. The urban expressway network consists of nodes and links with some loading elements. Each link is divided into several segments that capture variations of geometry and traffic conditions along the link. While most segments are defined in advance, additional segments can be dynamically created to capture the presence of incidents and the characteristic of the anisotropic mesoscopic simulation (AMS) model [16]. Nodes correspond to intersections. The loading elements and some nodes are origins and destinations (OD).

The complexity of the flows on the network is captured by integrating three classes of models. These classes include capacities associated with roadway features; incidents and intersection controls; deterministic queuing reflecting the effect of bottlenecks; and macroscopic speed-density relationships reflecting uninterrupted flow [17].

2.2. Capacities. Each segment has a capacity constraint at the downstream end referred to as the output capacity. The size of the output capacity depends on the section of the physical characteristics (such as width and slope) or unexpected events and control facilities and so forth. Each segment is divided into a moving part and a queuing part. The moving part corresponds to the section of the segment where vehicles can move with some speed. Queuing parts represent vehicles that are queued up. Vehicles are assigned to lanes according to their route leading to their destination. The determination of output capacities is based on recommendations from the Highway Capacity Manual (1994). When the queue length is equal to segment length, segment congestion occurs and a spill-back occurs on a segment.

2.3. Queuing. Queuing model is a set of models, each particular queue state (formation, disperse, obstruction, etc.) described by different models. For example, a vehicle will join in the queue which is dissipating, the position at the moment is

$$q(t) = q(0) + l(ct - m). \tag{1}$$

It is based on the delay of the ith vehicle in the queue given by

$$\frac{i}{c}, \tag{2}$$

where c is the output capacity of the segment. $q(0)$ is the position of the end of the queue at time $t = 0$. l is the average length of vehicles. m is the number of moving vehicles between the considered vehicle and the end of the queue at time $t = 0$. That is, m is the number of vehicles that reach the queue before the considered vehicle. Without loss of generality, it is assumed that the position of the upstream end of the segment is 0.

2.4. The Speed and Density Relationship Model. The speed model is based on the assumption that speed is constant on the upstream section of the segment, followed by a deceleration zone covering a downstream section, where the speed of vehicles varies linearly as a function of the position (see Figure 1). Of course, when the variable speed limit is applied, the speed would have been under the control of the prescribed speed value, because drivers tend to fast-forward, so the curve becomes parallel to the limit values.

The most basic model of mesoscopic traffic flow models is speed-density relationship model which means that the current vehicle's speed is determined by its population density of vehicles in front of a certain area. But the function curve is changed by adding variable speed limit and it becomes discontinuous function. The so-called variable speed limit is set the vehicle's speed limit value dynamically and science based on real-time traffic conditions and the current environment. It can be that the vehicle to maintain the economy

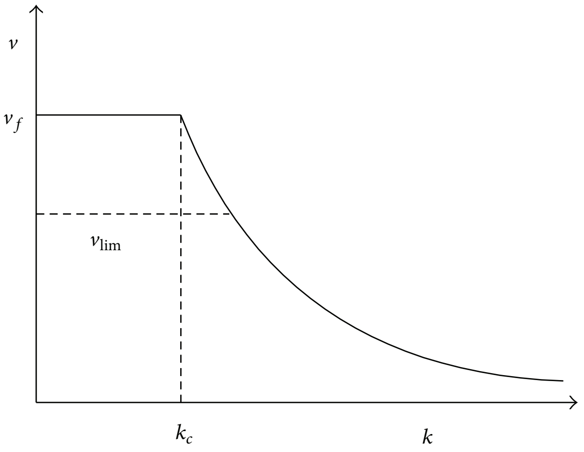

FIGURE 1: Speed and density relationship.

speed, to ensure a smooth density of road vehicles, or to maximize the road capability. It can also ensure traffic safety and avoid recurrent traffic jams by electronic information, data communications and computer processing technology. As the variable speed limit is introduced to the concept of traffic flow models means that the smaller speed is selected between the current vehicle speed and the limit speed. Often, the control strategy is the selected speed value. The following describes the models construction and application in detail.

We assume that the position of the upstream end of the segment is 0. Therefore, the downstream end is at position L, where L is the length of the segment. The speed function can then be written as

$$v(z)=\begin{cases}\min\left(v_u,v_{\lim}\right), & \left(0\le z\le L-L_s\right)\\ \min\left(\lambda\left(z-L\right)+v_d,v_{\lim}\right), & \left(L-L_s<z\le L\right),\end{cases} \tag{3}$$

where

$$\lambda=\frac{v_d-v_u}{L_s}. \tag{4}$$

The relationship of the speed density is

$$v=\begin{cases}\min\left(v_f,v_{\lim}\right), & \text{if } k\le k_c\\ \min\left(v_f,v_{\lim}\right)\left[1-\left(\dfrac{\max(0,\mathrm{k}-k_c)}{k_{\text{jam}}}\right)^{\beta}\right]^{\alpha}, & \text{if } k>k_c,\end{cases} \tag{5}$$

where v_u is the speed at the upstream end of the segment, v_a is the speed at the downstream end of the segment, and L_s is the length of the deceleration zone. v_f is the free-flow speed on the segment; $v_{\lim}$ is the value of the variable speed limit at h time period; k_{jam} is the jam density; k_c is the maximum permitted density under the free flow speed; k is the density; and α, β are parameters.

2.5. Vehicles Dynamics. In the segment of the moving parts, vehicle movement is driven by the speed-density relationship model and the vehicles being advanced based on the speed [1]. As for the deceleration zone, in the absence of a queue, the vehicle will reach position z at time $t(z)$, assuming that at time $t=0$ it is at position z_0 given by

$$t(z)=\begin{cases}\dfrac{1}{\lambda}\log\dfrac{\lambda_{z+v_u}}{\lambda_{z_0+v_u}}, & \text{if } v_u\ne v_d\\ \dfrac{z-z_0}{v_u}, & \text{if } v_u=v_d.\end{cases} \tag{6}$$

Assuming that at time $t=0$, a vehicle is at position z_0, its position at any time t is given by

$$z(t)=\begin{cases}e^{\lambda t}\left(z_0+\dfrac{v_u}{\lambda}\right), & \text{if } v_u\ne v_d\\ v_ut+z_0, & \text{if } v_u=v_d,\end{cases} \tag{7}$$

where λ is defined by (4).

Generally, the variable speed limit strategy will be implemented in upstream segments, so in the moving model the vehicle speed will be the smaller between v_u and $v_{\lim}$; thereby, the improved vehicle moving model is given by

$$z(t)=\begin{cases}e^{\lambda(t)t}\left(z_0+\dfrac{\min\left(v_u,v_{\lim}\right)}{\lambda(t)}\right)\\ \quad-\dfrac{\min\left(v_u,v_{\lim}\right)}{\lambda(t)}, & \text{if } t<t^*\\ q_0+l\left(ct-m\right), & \text{if } t>t^*.\end{cases} \tag{8}$$

In the presence of a queue the position $z(t)$ of a vehicle at any time t is given by

$$z(t)=e^{\lambda(t)t}\left(z_0+\frac{v_u}{\lambda(t)}\right)-\frac{v_u}{\lambda(t)}, \tag{9}$$

where

$$\lambda(t)=\frac{-v_u}{q_0+l\left(ct-m\right)}, \tag{10}$$

q_0, l, c, and m are defined by (1).

Similarly, we can give the corresponding model at the presence of queue:

$$\begin{gathered}z(t)=e^{\lambda(t)t}\left(z_0+\frac{\min\left(v_u,v_{\lim}\right)}{\lambda(t)}\right)-\frac{\min\left(v_u,v_{\lim}\right)}{\lambda(t)},\\ \lambda(t)=\frac{-\min\left(v_u,v_{\lim}\right)}{q_0+l\left(ct-m\right)}.\end{gathered} \tag{11}$$

2.6. The Anisotropic Properties of Mesoscopic Traffic Flow Processed. The anisotropic mesoscopic simulation (AMS) model is developed based on two intuitive concepts and traffic characteristics: (1) at any time, a vehicle's prevailing speed is influenced only by the vehicles in front of it, including those that are in the same or adjacent lanes and (2) the influence of traffic downstream upon a vehicle decreases with increased distance. These two characteristics define the "anisotropic" property of the traffic flow and provide the guiding principle for AMS model design. Based on such concepts, we define that for any vehicle i, only those leading vehicles (in the same lane or in the adjacent lanes) present in vehicle i's immediate downstream and within a certain distance are considered to influence vehicle i's speed response. This is a similar concept to a stimulus-response type of car-following model, with the distinction that in AMS, the stimulus of a vehicle's speed response is represented in a macroscopic manner instead of using intervehicle distance or speed as in microscopic models. In this paper, the method is to create a dynamic area of influence. For modeling purposes, the Speed Influencing Region (SIR) for vehicle i is defined as vehicle i's immediate downstream roadway section in which the stimulus is significant enough to influence vehicle i's speed response. This means that the current vehicle adjusts its speed according to the vehicles in front of it. So the AMS model complies with the anisotropic characteristics.

3. The Algorithm of Path Generating

Facing an urban road network with thousands of connections, it is required to complete the simulation of all vehicles (maybe tens of thousands or hundreds of thousands of vehicles) in real road network of 30–60 min in a relatively short period of 1–5 minutes. That is to say, in every 10–30 minutes, not only is the supply simulation realized, but also each vehicle's shortest path searching of time variation from the current location to its destination and its advance on this path are also required to be realized. It should be pointed out that the enhancement of calculation stability is just a part of the solution. A more reasonable approach is to divide the massive complicated issue into two relatively simple issues, such as output problem of an effective path which does not have a lot of requirements on real-time and storage and highly effective search problem of hyperpath information. In this paper, the idea of the algorithm is improved. That is the following. The number of paths between arbitrary OD pairs in a large-scale traffic network is very tremendous, but the effective number of paths is usually 4–10. We can see that there is not much sense in searching all the paths between OD pairs such as in traditional algorithm. Therefore, generating all the effective paths of the traffic network, storing in the memory, and directly searching the path for path data in the memory will greatly reduce the scale of the problem and improve efficiency of the system.

Algorithm is as follows.

Step 1. Set a valid path set $P = \phi$.

Step 2. Get the set of the effective paths under normal conditions and incorporate it in P: $P = P \cup k$ – shortest (G).

Step 3. Let the set of the temporary path $P_h = P$. For any path p in the P_h, for all $p \in P_h$, we implement the following operations.

For any one edge l in p, if l is not operated, we implement the following.

(a) Marked "processed";

(b) get the subgraph without the edge l, $G^* = G \setminus l$;

(c) generate a valid path set of G^* and incorporate it into the P: $P = P \cup j$ – shortest (G^*).

For details see Li et al. [18].

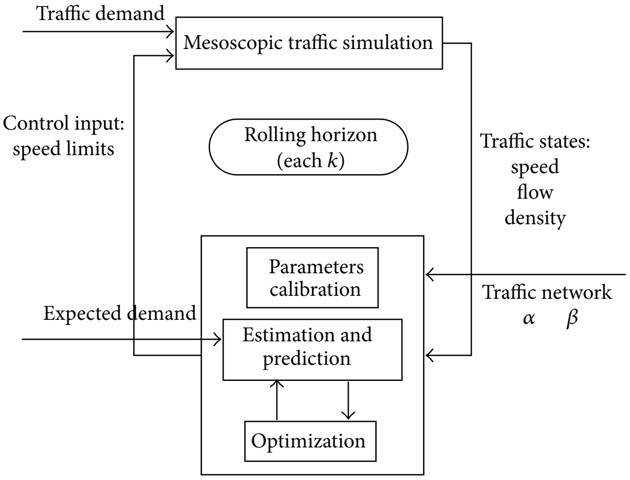

Figure 2: Simulation structure.

4. Simulation Method and Results

4.1. Simulation Method. In the following section, we demonstrate how the proper simulation with speed limits can be executed. We use a closed cycle scheme to solve the problem of simulation with variable speed limits (see Figure 2). In this scheme, at each time step, the optimal control speed limits are computed (by numerical optimization) over an estimation and prediction horizon. The parameter calibration horizon is used to improve the estimation accuracy including parameters in mesoscopic model, such as α, β, and k_{jam}. (After the parameter calibration horizon has been passed, the parameters are usually taken to be constant.) The procedure can reduce the number of variables and improve the stability of the system. A parameters calibration process is selected to correct system parameters, so as to obtain a more accurate and comprehensive description of the network and vehicle dynamic.

In the next time step, a new optimization is performed (with a prediction horizon that is shifted one time step ahead) and the estimation and prediction can be done for it. Their interaction can become a more comprehensive network state. This scheme, called rolling horizon, allows for updating the state from measurements or even for updating the model in every iteration step. By a simple test, at each level of demand, the output average network speed by using the proposed method is higher than that using DynaMIT or DynaSMART.

4.2. Simulation Environment. In this simulation, we take Jinan expressway network as an example. See Figure 3. This is a really traffic network, there is about 10 km from north to south and 11 km from west to east with 21 entrances and outlets. It is the main traffic artery of Jinan city. In the

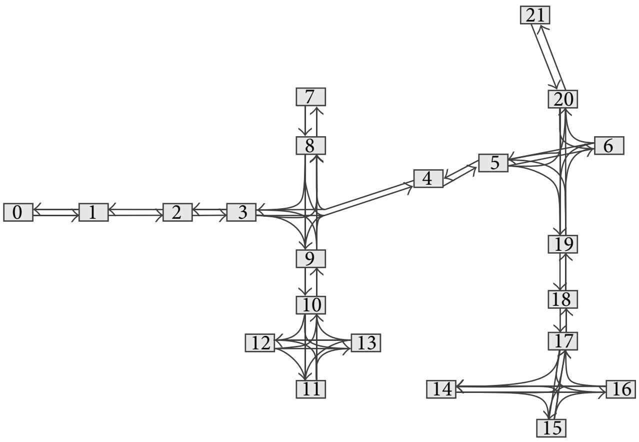

Figure 3: The Jinan expressway network.

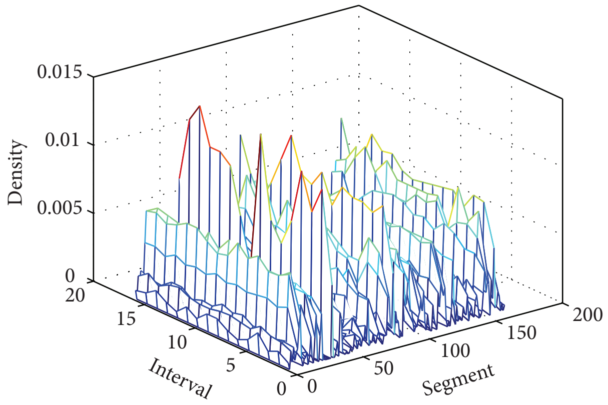

Figure 4: The average density on segment per interval at demand is 2.

network, the entrance is the place where the traffic demand appears or disappears, so we define them as OD points. One link between two nodes is defined as one segment at one direction. Each segment has two lanes. The marked nodes with numbers are defined as OD points. In this study, we focused on finding the discipline of traffic jam propagation and characteristic congestion propagation, so as to seek the solution for ease traffic congestion by variable speed limit method." is changed: The traffic congestion can be ease by the variable speed limit method. In the simulation model, we set the other uniform parameters for simplicity. The jam density is defined as 0.2486 pcu/m/L, α is 3.500, β is 0.75004, and the input and output capacity of segment are 0.6667 v/s. The dynamic OD estimation and prediction steps are 15 minutes. Because we focused mainly on urban expressway traffic network, the designed maximum speed is 80 km/hour without signal control at all intersection. The simulation interval is defined as 15 minute. The AMS is 150 meters. The total time of simulation is four hours; in other words, there are 16 time periods. Because we do not have the related real data, we must assume the OD demands; worthy of note is that it does not affect the nature of the problem in our analysis. The network OD demand is loaded with periodic closure boundary condition; namely, the same OD demand needs to be loaded on the network in each time period. In the simulation, due to the different demand levels, we set the variable speed limit scheme at upstream segment before the crowded section according to the actual situation, so as to ease the traffic congestion. We placed five variable message signs (VMS) on the traffic network of Jinan expressway according to the situation. The speed limit value is 60, 50, 40, 40, and 40, displayed on VMS, respectively, at different period. The simulation process is completed by single computer with 2 G memory.

4.3. Performance for the Network at Different Demand Levels. The benchmark is jam density on segment, which is divided into five equal parts. We named their status as very smooth, smooth, congestion, very congested, and jammed, respectively. If the most segments of the network have the above defined status, the network state can be deemed the same status.

Firstly, the OD demand is set to 2, most of the segments have not shown any phenomenon of congestion, so the network can be considered as very smooth status. At this demand level, the max vehicle number which can be loaded on the network is 659. In the simulation time period, the average density of the network is 0.0019 car/meter/lane, the average speed is 20.0751 mters/second, and all the flow of the network is 195705 vehicles. It is worth mentioning that the "average" is each segment at every interval. With the demand increasing, the network traffic becomes congested; for example, the demand is set at 3 and 5 between every OD pairs. Secondly, the OD demand is set to 3, at this moment some segments appear slightly crowded. The max vehicle number which can be loaded on the network is 1137. The average density increased to 0.0033 and the average speed is 18.8880. The network state is also smooth. The flow of the network is 302902 vehicles. This shows that the network loaded is greatly increased.

When the demand of all the OD pairs is set to be 5, the state of network becomes worse rapidly, which belongs to very congestion, almost jam state. The max vehicle number which can be loaded on the network is 2427. The average density and average flow on the segment become increased sharply, and the average speed is decreased smoothly. The mentioned data above become 0.0070, 504776, and 16.9355, respectively.

If the demand continues to increase, the network condition will become worse and worse. The network state shows extreme congestion. Some segments have become jammed and the load loses effectiveness. It is worth mentioning that the demand is increased by 1, the loaded vehicle is increased by 420 at every interval, so the loaded vehicle on the network is increased to 1680 in the simulation time, because we have 21 OD pairs and 16 intervals.

In this paper, the average density on each segment at every interval is used as the example to show the changes at different demand levels; see Figures 4, 5, 6, 7, 8, and 9.

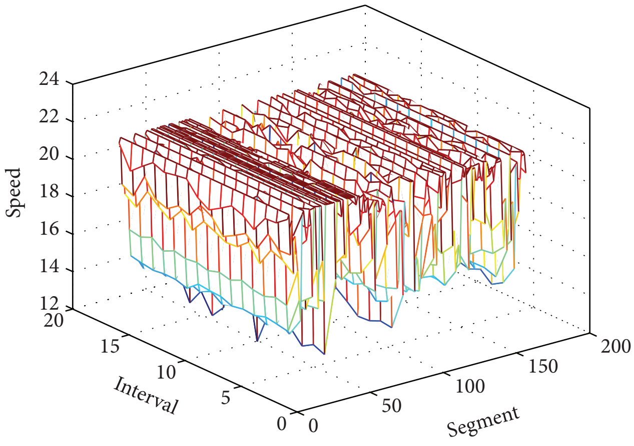

Figure 5: The average speed on segment per interval at demand is 2.

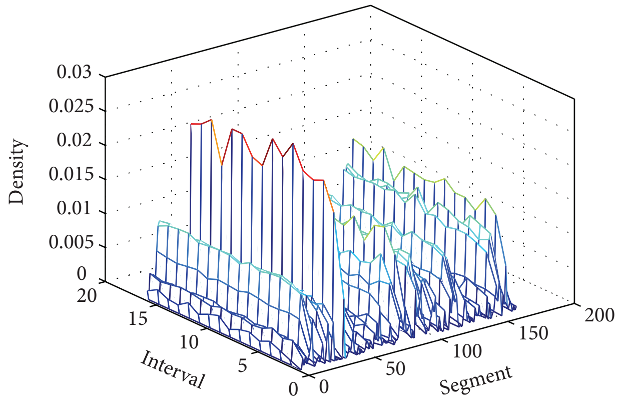

Figure 6: The average density on segment per interval at demand is 3.

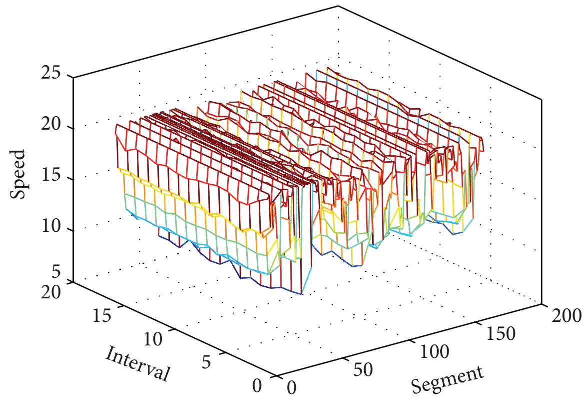

Figure 7: The average speed on segment per interval at demand is 3.

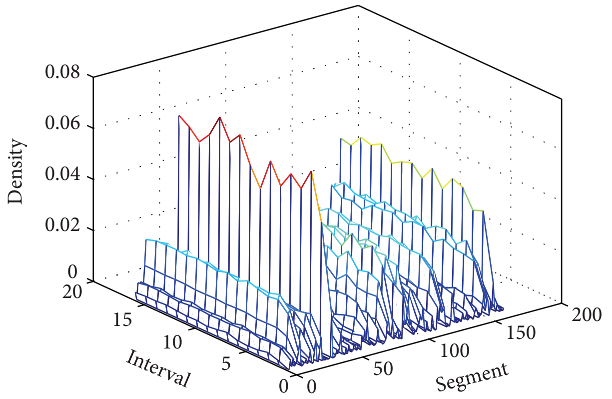

Figure 8: The average density on segment per interval at demand is 5.

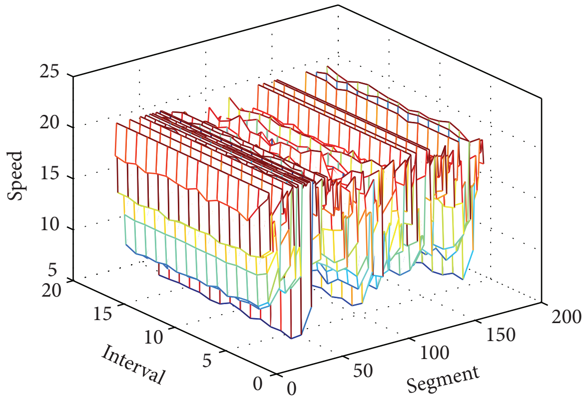

Figure 9: The average speed on segment per interval at demand is 5.

4.4. Performance for VSL Strategy. In the case of very smooth or smooth state, the vehicle's speed is almost free flow speed. There is no need to use variable speed limit measures which may make the network situation deteriorated. In the case of very congested or jammed state, the vehicle's speed is very slow and the variable speed limit has not effect. Therefore, the network with the demand 3 is used for balancing the traffic network conditions and achieving the purpose of smooth network. Four segments are selected to apply VLS strategy. The segments located between nodes 2 and 3 from west to east, between nodes 4 and 5 from east to west, between nodes 7 and 8 from north to south, and between nodes 9 and 10 from south to north are selected to install variable message signs. For simplicity, the uniform speed limit is designed as 60 km/h at 8:00~9:00, 50 km/h at 9:00~10:00, and 40 km/h at 10:00~12:00. The following we analyse the traffic dynamic of the area surrounded by the eight nodes and the four segments. The following we analyses the traffic dynamic of the area surrounded by the eight nodes including four segments which are installed VMS. The average density and speed are 0.0064 and 16.5636 before the VSL is applied. The total flow in the simulation time period is 13767 before the VSL is applied. But after the VSL is applied these data become 0.0076, 12.7650, and 13760. This illustrates that the variable speed limit strategy limits the segment's speed greatly. In the surrounded area, the average density and speed are 0.0077 and 15.3550 before the VSL is applied. The total flow in the simulation time period is 32629 before the VSL is applied. But after the VSL is applied these data become 0.0072, 15.3233, and 32579. This shows that the speed and volume of the area are

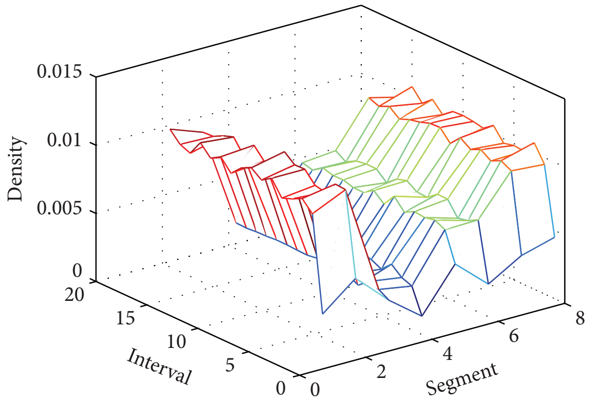

Figure 10: The average density on segment per interval before VSL.

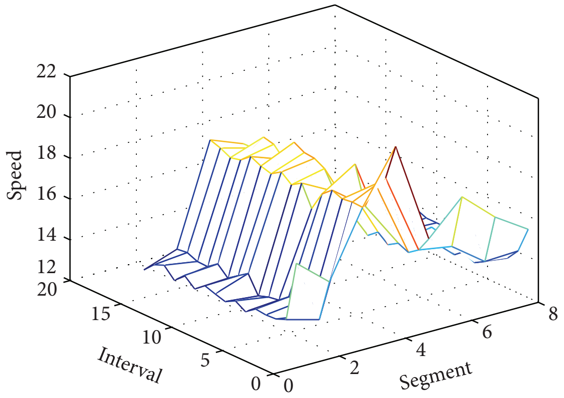

Figure 12: The average speed on segment per interval before VSL.

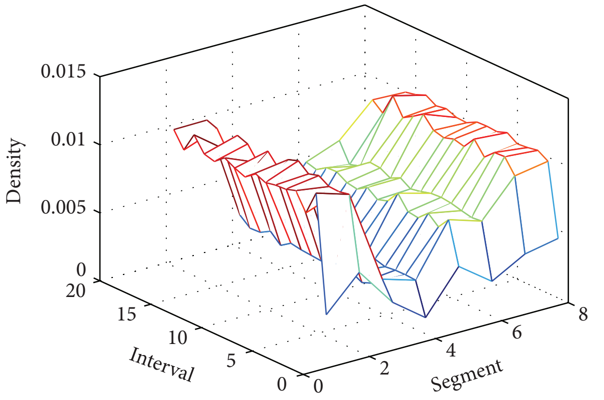

Figure 11: The average density on segment per interval after VSL.

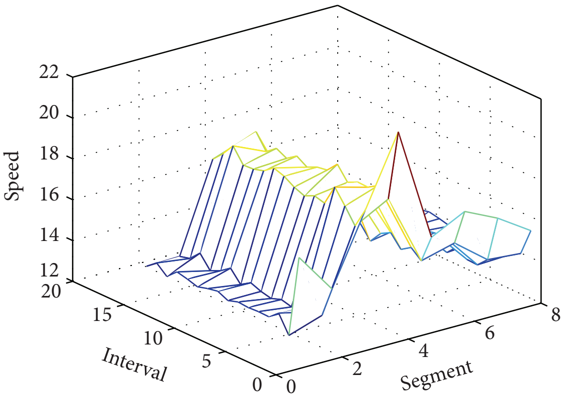

Figure 13: The average speed on segment per interval after VSL.

not changed more, but the traffic density is balanced. Figures 10, 11, 12, 13, 14, 15, 16, and 17 are comparisons between the variable speed limit that is applied or not.

The above discussion illustrates that the variable speed limit strategy can improve the traffic conditions of some areas. The typical applications of this situation is that if there is an accident which causes traffic jams somewhere on the traffic network, the variable speed limit strategy can be applied to ease traffic congestion. The urban roads and urban expressways are both considered simultaneously. The variable speed limit strategy can be implemented to ensure the maximum outlet flow or meet some certain standards from upstream segments so that the whole traffic network can achieve the optimal conditions.

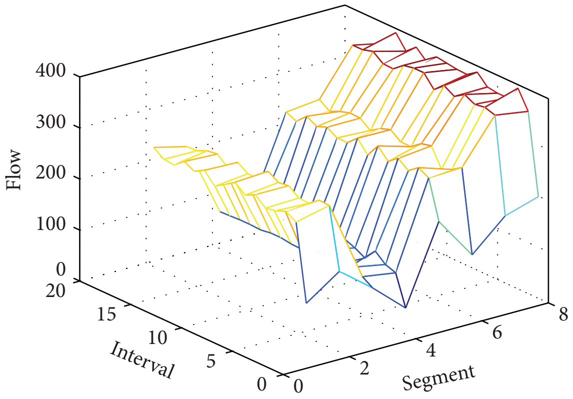

Figure 14: The average flow on segment per interval before VSL.

5. Concluding Remarks

In recent years, studying the problem of urban traffic system with dynamic traffic flow theory offers another new method to investigate the generation and propagation of traffic congestion. In this paper, the mesoscopic traffic flow model is improved which has been developed in the software DynaCHINA [19]. The simulation method is proposed also. Moreover we selected the average density, flow, and speed on a segment at every interval. Moreover we selected some indexes such as the average density, flow, and speed on a segment at every interval to analysis the dynamic of the traffic at different demand level. The results show that the model and method are reasonable and the variable speed limit strategy is effective. But the simulation is operated with idealized OD demand. In the real traffic system, we can acquire the related data, so the above assumption does not affect the nature of the problem. In addition, we can also study the congestion propagation property under the traffic accident, as well as

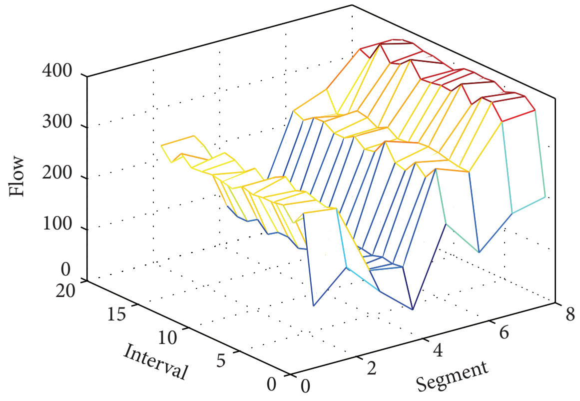

Figure 15: The average flow on segment per interval after VSL.

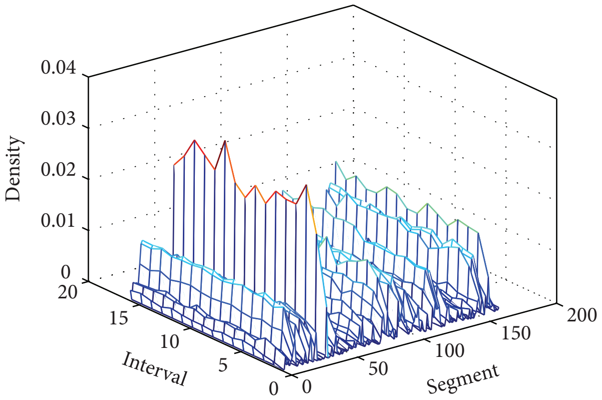

Figure 16: The average density on segment per interval before VSL of all networks.

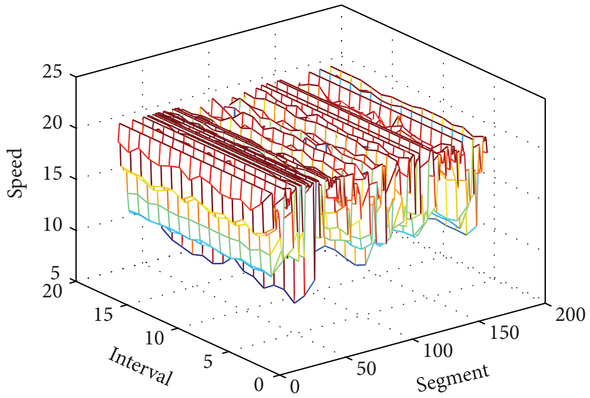

Figure 17: The average speed on segment per interval before VSL of all networks.

transportation planning simulation. The variable speed limit method is only one of many management strategies which will be a failure in some case. Therefore, it is necessary to consider other methods that can help ease urban traffic congestion, such as ramp control and optimal signal. Another method is message induction. The integrated method of the mentioned factors is the most effective method that can hope to alleviate growing traffic congestion. This is the content which is needed to continue to explore in the following papers also.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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