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Research Article

Traffic Multiresolution Modeling and Consistency Analysis of Urban Expressway Based on Asynchronous Integration Strategy

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The paper studies multiresolution traffic flow simulation model of urban expressway. Firstly, compared with two-level hybrid model, three-level multiresolution hybrid model has been chosen. Then, multiresolution simulation framework and integration strategies are introduced. Thirdly, the paper proposes an urban expressway multiresolution traffic simulation model by asynchronous integration strategy based on Set Theory, which includes three submodels: macromodel, mesomodel, and micromodel. After that, the applicable conditions and derivation process of the three submodels are discussed in detail. In addition, in order to simulate and evaluate the multiresolution model, "simple simulation scenario" of North-South Elevated Expressway in Shanghai has been established. The simulation results showed the following. (1) Volume-density relationships of three submodels are unanimous with detector data. (2) When traffic density is high, macromodel has a high precision and smaller error and the dispersion of results is smaller. Compared with macromodel, simulation accuracies of micromodel and mesomodel are lower but errors are bigger. (3) Multiresolution model can simulate characteristics of traffic flow, capture traffic wave, and keep the consistency of traffic state transition. Finally, the results showed that the novel multiresolution model can have higher simulation accuracy and it is feasible and effective in the real traffic simulation scenario.

1. Introduction

With the rapid development of social economy and the accelerating process of urbanization, traffic demands increase sharply and traffic-related problems have become the common challenges for countries in the world. In order to solve the above questions, it depends on the comprehension and its application of the traffic control and operating rules. According to the size of the granularity, traffic simulation system is usually divided into three levels, that is, macroscopic traffic simulation, mesoscopic traffic simulation, and microscopic traffic simulation.

In the early 1960s, many macroscopic traffic simulation model emerged in the traffic simulation field [1], and a certain application of the results was achieved. But the macrosimulation model has difficulty in expressing the real dynamic behavior of the crowded state of traffic flow properly and each system performance change cannot be described which is caused by the random phenomenon of traffic flow. Since the 1980s, mesoscopic traffic models have been proposed and have been part of the application. Mesoscopic model cannot reflect the single driver's reaction to information and effects of different control systems to road network can only be expressed in the form of the capacity [2]. With the development of computer technology and system simulation technology, microscopic traffic simulation has been widely used. However, due to the complexity of microscopic modeling, uncertainty of parameter calibration, and constraints of computing resource, the network range of microsimulation is generally small [3]. It can be seen that single resolution model cannot simultaneously solve a series of issues, such as an actual operating state description of traffic flow, operating state description of a single vehicle, simulation accuracy, simulation complexity, and limited resources [4].

With the expansion of the scale of the traffic network simulation and simulation accuracy, a single fixed resolution simulation model cannot effectively solve the contradictions between network complexities and limited resources [5]. Thus, ideas and methods of multiresolution traffic simulation were proposed. Multilevel traffic hybrid simulation model system can be formed by using multiresolution modeling technology, which can organically integrate all levels of traffic simulation models and play their respective advantages of each model. At the same time, the original intricate problem will be solved by using multigranularity analysis methodology. Therefore, the paper studies the traffic multiresolution modeling and its consistency analysis of urban expressway main line and its ramp. It provides a feasible and effective method in the way of multiresolution theory applied in the field of traffic. And it points out a new direction for the further study of multiresolution theory.

2. Overview of Multiresolution Traffic Simulation Model

According to different granularity level of the hybrid model, multiresolution traffic simulation model can be divided into two aspects, "two-level hybrid model" and "three-level or above hybrid model." They are introduced as follows.

2.1. Two-Level Hybrid Models

2.1.1. Macroscopic and Microscopic Hybrid Traffic Models. The main idea of macro- and microhybrid traffic model is to simulate the entire road network by macromodel and only parts of the roads or subnetwork by microsimulation model and to perform polymerization and depolymerization at the boundary of microscopic model. The main representative studies of such models are described below. Lerner et al. [6] (2000) achieved a hybrid model which combined PELOPS microscopic model and macroscopic models SIMONE. In the paper, he discussed the random depolymerization method from the macromodel to the microscopic model and the polymerization process from micro- to macromodels. Magne et al. [7] (2000) integrated SITRAB + (microscopic model) with SIMRES (macroscopic model) and focused on the five limit items which can be simultaneously met by the car-following models and macroscopic models, so as to explore the compatibility of macromodel and micromodel. Leclercq [8] (2007) proposed macro- and microhybrid model based on the principles of Lighthill–Whitham–Richards (LWR) model. In the paper, consistency and conversion issues were discussed between macroindicators and microindicators. On the basis of the Asymmetric Cell Transmission Model (ACTM), improvement of Traditional Cell Transmission Model (CTM), Torné et al. [15] (2014) proposed an elegant analytical relationship based on traffic flow theory, which can ensure the physical consistency of the dynamics involved in queue processes in the proximity of a noncontrolled merge junction on freeway. Such models focused on theoretical consistency between macro- and micromodel but did not pay attention to advantages of different resolution model.

2.1.2. Mesoscopic and Microscopic Hybrid Traffic Models. The main idea of mesoscopic and microscopic hybrid traffic model is to simulate part of road network by mesomodel and micromodel and achieve conversion between mesomodel and micromodel by specific means at boundary nodes. Study of such models is the current hotspot of traffic hybrid simulation system.

Early research results included the hybrid model about PARAMICS microscopic model and DYNASMATR mesoscopic model, implemented by Sahraoui et al. [9] (2001), which emphasized that the microscopic model is not suitable to describe the route choice behavior. Nizard [10] (2002) focused on calibrating the mesoscopic model by using the results of microscopic simulation model and implemented a hybrid model of microscopic MITSIMLab and Metropolis mesoscopic model. Burghout [11] (2004) achieved the compound of microscopic model MITSIMLab and mesoscopic model Messo, which discussed not only the boundary interface problem of two kinds of model but also the dynamic path selection method based on virtual road sections. Ziliaskopoulos et al. [12] (2006) implemented the mixing of mesoscopic CTM model and microscopic discrete car-following model. Nava et al. [16] (2012) documented the modeling efforts in regard to a dynamic lane closure and reversible lane operation by integrating microscopic and mesoscopic model. Joueiai et al. [14] (2015) provided a brief overview of mesoscopic LWR model and its solution by the Variational theory. It is the central issue of current traffic hybrid simulation system but it has some disadvantages, such as being based on the interaction of cross-resolution, poor scalability, and instability caused by high coupling of system.

At present, traffic hybrid models have received more and more attention by scholars and there are some achievements in all aspects of the traffic field. The main representative studies of two-level hybrid model are described in Table 1.

Two-level hybrid traffic model, usually integrated with two different granularity simulation models, which can take full advantage of different models, overcome or reduce the disadvantages of single model and maximize to meet the needs of applications. However, with the development of the actual traffic demand, a simple two-level hybrid model cannot meet the demands of reality. In order to meet the practical applications and increasing theoretical research, multiresolution traffic hybrid model is the future direction of development and research focus, which uses the more rational modeling idea and method.

2.2. Three-Level and above Hybrid Traffic Models. The traditional integrated model approach is suitable for the two-level hybrid models, but it is a little insufficient to build three-level or above hybrid models. Multiresolution modeling (MRM) is an international research focus in the field of modeling and simulation since the 1990s. MRM has become one of the key

Table 1: Two-level hybrid simulation models and its characteristics.

Number	Model name	Level	Time	Characteristics
1	Lerner et al. [6]	Integration of macro- and micromodels	2000	Integration of micromodel PELOPS and macromodel SIMONE
2	Magne et al. [7]	Integration of macro- and micromodels	2000	Integration of micromodel SITRAB+ and macromodel SIMRES. Focus on compatibility of microscopic and macroscopic model
3	Leclercq [8]	Integration of macro- and micromodels	2007	Integration of macromodel LWR and its micromodel. Consistency and conversion of parameters
4	Sahraoui et al. [9]	Integration of meso- and micromodels	2001	Integration of micromodel PARAMICS and mesomodel DYNASMATR
5	Nizard [10]	Integration of meso- and micromodels	2002	Integration of micromodel MITSIMLab and mesomodel Metropolis
6	Burghout [11]	Integration of meso- and micromodels	2004	Integration of micromodel MITSIMLab and mesomodel Messo
7	Ziliaskopoulos et al. [12]	Integration of meso- and micromodels	2006	Integration of mesoscopic CTM model and microscopic discrete car-following model
8	Xu et al. [13]	Integration of macro- and micromodels	2010	Traffic flow analysis of dynamic network; real-time traffic prediction
9	Joueiai et al. [14]	Integration of meso- and micromodels	2015	Investigate the influence of various boundary conditions on traffic features

technologies for large-scale simulation of the United States Navy. United States National Research Council consider that MRM is one of the fundamental challenges of the modern modeling and simulation techniques [17].

2.2.1. Multiresolution Modeling Method. In the study of MRM, the modeling method is one of the key contents and the method provides a methodological basis for the multiresolution traffic simulation. Among modeling methods, there are some influential theories such as Aggregation/Disaggregation, Select Viewing (SV), UNIFY method, Integrated Hierarchical Variable-Resolution Modeling (IHVR), and Cross-Resolution Interaction. They are not going to be described here in detail.

Aggregation and Disaggregation method is easy to understand, but there are some problems, such as transient characteristic inconsistencies and chain disaggregation [18, 19]. Select Viewing method is relatively simple. It is easy to maintain consistency between the models but its calculation cost is too large and its flexibility is poor [20, 21]. UNIFY method can avoid disadvantages of Aggregation and Disaggregation and ensure consistency between the different resolution models; however, the efficiency of UNIFY is very low and the resource consumption is huge [21, 22].

IHVR method is a process-oriented approach and is easy to understand, but it is difficult to choose the variables because the hierarchical relationship between variables is not strict [23]. Alternate Submodels need higher interface requirements for the models and its reusability and transformation are poor because of its fixed resolution [24]. Only one submodel is active in the course of simulation at a time, which leads multimodel formalism to have status recovery and synchronization problems [25]. Cross-Resolution Interaction method can use independent simulation models on different resolution levels, which is not only to retain the advantages of the original model but also to maintain loose coupling between the models [26]. It reduces system cost while improving the stability of the simulation system scalability.

Therefore, the article will use Cross-Resolution Interaction method in the study of multiresolution traffic modeling.

2.2.2. Multiresolution Traffic Model. Currently, multiresolution modeling theory is not very mature, but there have been some successful applications, which highlights the fact that the multiresolution modeling has broad prospect and research value. In the field of multiresolution modeling applications, the representative work includes the following. Davis and Hillestad (1998) presented an exploratory analysis based on multiresolution model by using multiresolution modeling theory [27]. Lee and Fishwick (1999) studied the multiresolution modeling applications in real-time systems [28]. Sekine et al. (2001) studied the multiresolution modeling in Traffic System Simulation [29]. Schaffer and Kukolich (1998), Schaffer and Marion (1999), and Butler (2002) studied the multiresolution modeling in comprehensive natural environment [30–32]. Reynolds et al. [33] (2002) studied the meteorological and oceanographic multiresolution modeling problems and so on.

Since the middle of 1990s, China began to study multiresolution modeling theory and its application in the field of combat simulation aspect, but the research is not systematic. In recent years, traffic multiresolution simulation models have been studied widely, but all of them are in their first step. Currently, representative research in the field of multiresolution traffic simulation is Transmodeler [34] (Yang and Slavin, 2002), which is a package of a famous traffic simulation/planning software—TransCAD. Transmodeler integrated the three granularity traffic models—macroscopic traffic model, mesoscopic traffic model, and microscopic traffic model. User can freely select the granularity of sections, simultaneously choose different granularity simulation model in different sections, and keep the simulation system in different granularity running concurrently. Transmodeler can maintain balance among simulation granularity, computing speed, evaluation indexes, and system overall performance. It can meet the specific requirements of simulation program very well. However, multiresolution modeling research is just emerging, especially in the field of transport; there is no relevant systematical academic literature. It also illustrates the importance and feasibility of the multiresolution traffic simulation study.

2.3. Comprehensive Analysis and Commentary. First of all, in a single resolution traffic model, the macroscopic model has a high computational efficiency and low computing requirements, but it is not suitable to simulate this traffic behavior, which needs to consider the interaction between adjacent vehicles. Microscopic model can simulate the movement behavior of a vehicle and visual simulation process, which is in favor of the simulation results analysis. However, road network modeling of microscopic model is so complex, the model is highly sensitive, and it requires a high computing ability. Mesoscopic model is studied on vehicle fleet and it can describe the interaction between the vehicles to some extent. Computing ability requirement of mesoscopic model is lower than microscopic models', but it needs a good balance between width and depth of simulation.

Secondly, the two-level hybrid model based on different granularity is generally achieved by parameters conversion method, which combines the advantages of a single model to some extent. However, the applicability of two-level hybrid model is rather poor, basic data processing is complex, and its expansibility is relatively weak. Three-level or above multiresolution mixed traffic model is based on multiresolution modeling theory and it not only integrates the advantages of multiple models, but also provides a shared basic database in order to save data maintenance cost for a single model, which ensures the consistency between models. Features comparison between the different models is shown in Table 2 [5, 35].

In summary, traffic simulation theory and models have made many achievements, but there are still some shortcomings, mainly reflected in the following aspects.

(1) In terms of defining the concept, macroscopic model, mesoscopic model, and microscopic model of multiresolution modeling are a relative concept. For example, models can be distinguished obviously when establishing multiresolution model by Aggregation and Disaggregation method. It can be distinguished clearly between macroscopic model and microscopic model when modeling by other methods; however, mesoscopic model is difficult to distinguish from granularity. Therefore, how to define different resolution models is worthy of deep researching.

(2) In the study objects aspect, most models are aimed at freeway or highway, less at urban expressway. Meanwhile, models proposed by foreigners need to be verified in the Chinese traffic situation because of different transport infrastructure, traffic composition, traffic control means, and characteristics of traffic participants.

(3) In terms of granularity, most models focus on single resolution model, which is modeling on a certain level of granularity, while less studies are focused on multiresolution model, especially three-level or above multiresolution models. At the same time, the study of integrated manner and type and directions of hybrid models have been less mentioned.

(4) In terms of theoretical foundations, different types of models have different theoretical basis; at the same time, the hybrid model has a number of different theoretical bases. Without a systematic theory, most hybrid models are based on conventional parameter transformation or partial data sharing. However, multiresolution simulation theory provides a new idea and theoretical basis for the hybrid model. But all the multiresolution simulation theories and their application in traffic are still in their infancy.

(5) In research methods, most previous hybrid models are based on interface parameters fusion method, whose case study is often an ideal or specific scene, and it is difficult to apply to practical problems. Aggregation and Disaggregation method, a common multiresolution modeling method, is more suitable for nonmemory system. However, Cross-Resolution Interaction is suitable for multiresolution traffic simulation system with memory function. In addition, Cross-Resolution Interaction can be integrated with integration simulation theory, providing a consistent methodology basis for mixing different resolution models, and it can make better use of existing research results and save costs.

(6) In terms of model implementation, existing models have too much control parameters and do not consider the actual traffic road conditions, which require adjusting, modifying, and improving the models under ideal conditions.

(7) In model optimization aspect, existing models' solving processes are too simple and the results accuracy is not high; the algorithm efficiency is relatively low, which cannot meet traffic simulation real-time and accuracy requirements. In maintaining the accuracy of the algorithm, parallel algorithm can greatly improve the efficiency of computing, which provides a feasible way to achieve real-time simulation.

(8) In model validation aspect, most models are based on purely mathematical derivation and lack of effective actual data validation and verification, which results in the model having a certain difference with the actual traffic situation.

3. Multiresolution Traffic Simulation Model and Its Framework

3.1. Definition of Model Resolution. Model resolution still does not have a very clear definition. International Simulation Interoperability Standards Organization defined resolution as detailed and accurate representation of the real world level in the models and simulation, which can be also called granularity [36]. Resolution's definition by Roza et al. was to describe the accuracy and precision of some models and simulation applications in the real world [37]. Granularity and level of detail are equivalent to the concept of resolution in the field of modeling and simulation [17].

Table 2: Comparative analysis of different resolution traffic simulation models.

Item	Single resolution traffic simulation model			Multiresolution traffic simulation model	
	Microscopic model	Mesoscopic model	Macroscopic model	Two-level hybrid traffic model	Three-level and above hybrid traffic model
Theoretical background	Discrete event system modeling, fixed-step	Discrete event system modeling, fixed-step	Continuous system modeling, numerical simulation	Similar to the distributed simulation	Multiresolution modeling and simulation theory
Simulation object	Single vehicle	Single vehicle, driven by queue	Vehicle is regarded as fluid or gas	Depending on the hybrid model	Objects can be dynamically changed on demand
Core model	Car-following model, lane changing model, cellular model	Queuing model, flow-velocity-density model, allocation model	To describe the system evolution rule in differential equations derived from the flow conservation	Mathematical derivation or interfaces defined in original model	Integration of consistency maintenance of different resolution models
Implementation	Time series method, event-based method	Numerical methods, time series method, event-based method	Numerical methods	Parameter conversion, partial data sharing	Integrated simulation, multiresolution modeling method
Application	Microdesign analysis such as intersection channeling and signal timing	Dynamic network simulation, but limited to the scope of the network	Planning analysis of large-scale road network	Depends on hybrid models	Gradual application from network to regional to intersection
Typical system	VISSIM, Aimsun, PARAMICS, CORSIM	Dynasmart, DynaMIT, Dynameq, Transims	NETFLO2, FREFLO	DynaCHINA	Transmodeler

According to the range scope of granularity, multiresolution model can be divided into low-resolution model (macroscopic model), normal resolution model (mesoscopic model), and high-resolution model (microscopic model) [36]. Under normal circumstances, you can use a high-resolution model to describe the microscopic properties of the system, the low-resolution model to describe the system of macroscopic properties, and normal resolution model to describe application scenarios that need to balance simulation accuracy and breadth, so that you can effectively reduce computing costs and increase operating efficiency.

3.2. Multiresolution Model. In theory, multiresolution traffic model is a mathematical description of the same object under different granularity. From the view of practical application, different people pay attention to different aspects for the same issue, and different granularity models are built according to different needs. In addition, the establishment of different resolution models' family of transportation research objects can enable the user to choose different resolution models based on specific needs.

In this paper, transportation system multiresolution model is created by Set Theory. The model describes the characteristics of the system, including behavioral characteristics, time characteristics, spatial characteristics, performance characteristics, granularity level, and internal structure. In the model formalization process, set structure of research objects is built through sufficiently abstracting the transportation system characteristics, so that the model has a more extensive description and scope. The paper draws seven-tuple structure to build a multiresolution model of ten-tuple structure of transportation system and discusses the state transition equation and the mechanism of traffic state [38, 39]. So, multiresolution traffic simulation model based on Set Theory is described as follows:

$$M = \langle X, Y, T, \Omega, S, \theta, Q, \delta, \Gamma, \lambda \rangle . \quad (1)$$

Among them, M represents a traffic system.

X indicates the input set of the system, which describes the effect of the external environment on the system. Generally, X represents input variables of real value. If external input is a discrete event, X can be described as $X_e \cup \{\phi\}$, in which X_e is a set of external events and ϕ is a set of empty events. In a specific traffic scene, X_e may be represented as speed, density, and so on.

Y indicates the output set of the system, which describes the sum of the output of the system to the external environment. In a specific traffic scene, it may represent the parameter, such as traffic flow and location.

T is a time coordinate system to describe the system time change. According to T, system is divided into discrete-time system or continuous-time system.

Ω is time input segment set, which describes the system input mode in a time interval. It can be described as $\omega : \langle t_0, t_1 \rangle \rightarrow X$. $\langle t_0, t_1 \rangle$ is an interval of time base from the initial time t_0 to terminate time t_1. The set of all input fragments in $\langle t_0, t_1 \rangle$ are denoted by (X, T). Ω is a subset of (X, T). (1) When T is a set of real numbers, Ω is divided into two cases. ① Ω is piecewise continuous segment set, which can be described as $\omega : \langle t_0, t_1 \rangle \rightarrow X$, $X = R^n$. ② Ω is discrete events section set, which can be described as $\omega : \langle t_0, t_1 \rangle \rightarrow X_e \cup \{\phi\}$. If limited event time collection $\{\tau_1 \cdots \tau_n\} \not\subset \langle t_0, t_1 \rangle$, then $\omega(t) = \phi$. (2) When T is a set of integers, Ω is finite set of time series.

S is a spatial coordinate to describe the system spatial location. According to S, system is divided into discrete space system or continuous space system.

θ is spatial input segment set, which describes the system input mode in a spatial interval. It can be described as $\varphi : \langle s_0, s_1 \rangle \rightarrow X$. $\langle s_0, s_1 \rangle$ is an interval of space base from the initial position s_0 to terminate position s_1. The set of all input fragments in $\langle s_0, s_1 \rangle$ are denoted by (X, S). θ is a subset of (X, S). (1) When S is a set of continuous values, θ is divided into two cases. ① θ is piecewise continuous segment set, which can be described as $\varphi : \langle s_0, s_1 \rangle \rightarrow X$, $X = R^n$. ② θ is discrete events section set, which can be described as $\varphi : \langle s_0, s_1 \rangle \rightarrow X_e \cup \{\phi\}$. If limited event spatial collection $\{\gamma_1 \cdots \gamma_n\} \not\subset \langle s_0, s_1 \rangle$, then $\varphi(s) = \phi$. (2) When the values of S are not continuous, θ is finite set of space series.

Q is the collection of internal state, which is the core of the internal structure modeling. It is a collection of information under a certain state of the system, and it affects the system behavior response of the present and the future. In a specific traffic scene, it may characterize all parameters of the traffic operation.

δ is state transition function, which defines how the internal state of the system changes. It can be described as $\delta : Q \times \Omega \times \theta \rightarrow Q$. System state is q when it is in position s_0 at time t_0. When an input segment $\omega : \langle t_0, t_1 \rangle \cup \varphi : \langle s_0, s_1 \rangle \rightarrow X$ is applied to q, $\delta(q, \omega, \varphi)$ represents the state of the system in position s_1 at time t_1. Thus, the internal state at any moment, the time input section, and space input section from that moment all determine the status of the position of the segment end time. δ can be simply divided into macroscopic traffic model, mesoscopic traffic model, and microscopic traffic model in multiresolution traffic simulation model. Different resolution traffic model controls the system internal state changing of different granularity and output the corresponding results. In the paper, different resolution model is referred to as traffic model. Submodel is defined as one-part model of the set of multiresolution models. Specific forms of each submodel are described below.

Γ is granularity function, which describes the level of granularity of the system's internal state. It can be described as $\Gamma : Q \rightarrow \delta$. Granularity function gives the standard of state transition function, which is $\Gamma : Q \times X \times T \times S \rightarrow \delta$. In a specific traffic scene, it may be the parameters of the model at different resolutions or mouse operation.

λ is output function, which can be described as $\lambda : Q \rightarrow Y$. Output function gives an output section, which is $\lambda : Q \times X \times T \times S \rightarrow Y$. In a specific traffic scene, it may be the formatted input operation of database.

The set structure based on ten dimensions can describe the properties and behavior characteristics of the object by time, space, and corresponding parameters. The multiresolution traffic model can be effectively described by Set Theory and it provides a basis for the study of the establishment and evaluation of complex models of different resolutions transportation system.

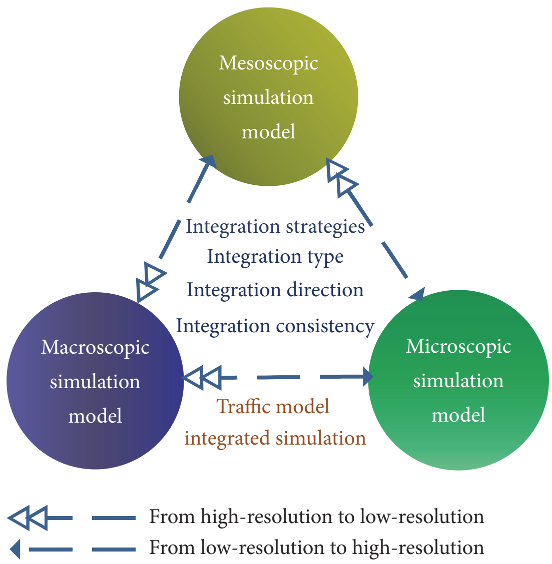


Figure 1: Triangular framework of multiresolution traffic simulation model.

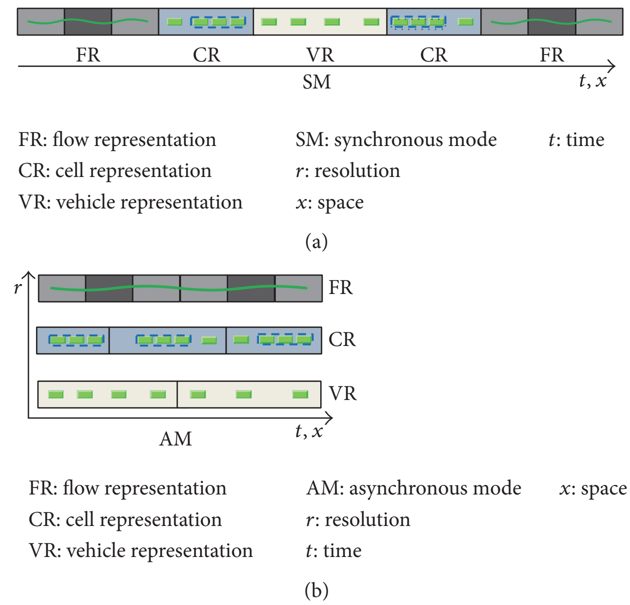


Figure 2: Multiresolution traffic simulation integration strategies schematic diagram.

3.3. Multiresolution Traffic Simulation Framework. Using the integrated simulation methods to achieve multiresolution traffic simulation system is the feasible and optimum method, both from the point of view of an implementation convenience or the cost. On the one hand, it can make full use of existing resources and systems, to avoid resources waste and to maintain the continuity of the existing application system. On the other hand, it can greatly reduce development and testing costs, meanwhile meeting the target needs of system.

Multiresolution traffic simulation model can be established and analyzed from the macromodel, mesomodel, and micromodel three granularity levels. The three granularity level models can be fused, analyzed, simulated, and experimented by integrated simulation methods from aspect of integration type, integration strategy, integration direction, and integration consistent, and so on. All of these build a multiresolution traffic simulation triangular framework, shown in Figure 1.

Multiresolution traffic simulation triangular framework makes the macro-, meso-, and micromodel as its vertexes, which are the basis and cornerstone of multiresolution traffic simulation. Traffic model integrated simulation method in the triangular framework, as a means, is fusion technology basis of different resolution simulation models. Integration type, integration strategy, integration direction, and integration consistent are the cores of different resolution simulation model in optimization process. All the above parts are the foundation of multiresolution traffic simulation in verification and validation process.

3.4. Integration Strategies of Multiresolution Simulation. There are different integration strategies when integrating macroscopic, mesoscopic, and microscopic simulation models. According to time standard, it can be divided into Synchronous Mode (SM), Asynchronous Mode (AM), and Mixing Mode (MM). SM is a serial execution policy in essence, which is a process that is different from granularity models combined in a certain order that can run sequentially. AM is that different granularity models that can run simultaneously in a certain space or time and it is a parallel execution strategy. MM is a mixed application of SM and AM. SM is used in part of the space or a period of time, while AM is adopted at other space or time. MM can maximally meet the actual simulation needs and make full use of the advantages of both integration strategies.

Figure 2 is a schematic view of the multiresolution traffic simulation integration strategies. Figure 2(a) shows a serial operation mode of macromodel (Flow Representation, FR), mesomodel (Cell Representation, CR), and micromodel (Vehicle Representation, VR), which is an implementation of SM. Figure 2(b) shows a parallel operating mode of macroscopic, mesoscopic, and microscopic model, which is an implementation of AM. In this paper, AM is used. Please refer to another article literature of the author [40] if studying SM.

4. Macroscopic Traffic Flow Modeling and Simulation Analysis

4.1. Urban Expressway Traffic Characteristics and the Target of Macroscopic Modeling. The main purpose of urban expressway is to build fast connecting channels between the various functional areas within the city, between functional areas and periurban satellite town, and between neighboring cities and functional areas. Urban expressway can separate vehicles from nonmotor vehicle in travel space [41]. Compared with other roads, urban expressway has its own features in the aspect of road environment, traffic flow characteristics, and other aspects.

(1) Main line of urban freeway is fully enclosed in the form of grade separation. So its traffic flow of main line is rapid and continuous, while relief road, affected by intersection traffic control, is typical intermittent traffic flow and queuing and fleet dissipate phenomenon occurs regularly [42].

(2) Urban freeway mainly services the vehicles in the city or a short travel.

(3) In general, design speed of freeway is 60–80 km/h, no more than 100 km/h, in China.

When vehicles number is small on urban freeway, the vehicle can run in expected speed limits as a free flow. With the increase of traffic flow and traffic density, traffic driving speed slows down and results in queuing.

(4) Urban expressway has plenty of entrances and exits, the distance between the entrances and exits is small, and its density is a little high.

(5) Operating speed of urban expressway is basically in normal distribution. At the entrance of ramp, the vehicle speed is relatively concentrated, which is general in skewed distribution [43].

(6) Compared with urban roads, capacity of urban freeway is larger and the average operating speed is bigger. Urban freeway has obviously tidal characteristics.

In this paper, urban expressway has been studied. According to analyzing the properties of urban expressway, macroscopic model should describe traffic flow characteristics of the following aspects. ① Describe the viscous and compression properties of traffic flow. ② Describe the characteristics of the external environment and driving characteristics of the drivers. ③ Simulate various actual traffic flow phenomena, such as traffic congestion caused by accident or construction. ④ Reflect the ramp signal control and no ramp metering impact on transportation state. ⑤ Describe the traffic flow operating state variation with time in the basic segment road, entrance and exit of ramps, and weaving section.

4.2. Macroscopic Mathematical Model of Traffic Flow

4.2.1. Hypothesis of Macromodel. For macroscopic model, make the following basic assumptions for the relationship between speed and density of traffic flow:

(1) Speed ranges from zero to free-flow speed $u_f(x,t)$; density ranges from zero to jam density $k_{\text{jam}}(x,t)$.

(2) When the space between vehicles is infinity, vehicle speed is limited to free-flow speed; that is, $\lim_{k\to 0} u = u_f(x,t)$, wherein k is traffic density and u is velocity.

(3) When the density is jam density $k_{\text{jam}}(x,t)$, the speed is zero; that is, $u(k_{\text{jam}}) = 0$.

(4) The vehicle speed decreases with the increase of density; $u'(k) < 0$ $(0 < k \le k_{\text{jam}}(x,t))$.

(5) Equilibrium speed function $u_e(k)$ satisfies the following formula. $u_e'(k) < 0$, $(ku_e(k))'' < 0$, $u_e(0,x,t) = u_f(x,t)$, $u_e(k_{\text{jam}}(x,t)) = 0$. According to the actual situation, different road sections have different free-flow speed $u_f(x,t)$ and different jam density $k_{\text{jam}}(x,t)$.

(6) The driver's response to stimulation has a time delay T_r, which can be constant or function.

(7) Equilibrium speed is $u_e(k,x)$ and speed reaction time is $(t+T_r)$ at $(x+\Delta x)$ position.

(8) The state change of rear vehicle depends on the relative speed of adjacent vehicles, the space between adjacent vehicles, viscous resistance caused by vehicle type difference, compression properties of traffic flow, and drivers' psychological vehicle safety distance.

4.2.2. The Derivation of Macromodel. Based on the above assumptions, combined with the derivation of the classical car-following model [44–46] and the observation of car-following phenomena [47], the macromodel should consider acceleration caused by relative speed difference of the adjacent two vehicles, viscous resistance caused by braking distance, difference of the adjacent two vehicles, compression properties of traffic flow caused by drivers' psychological vehicle safety distance, and actual transportation environment. And state of rear vehicle depends on the space between the adjacent vehicles.

For the two adjacent car-following vehicles, $x_n(t)$ is the position of vehicle n at the time t. $x_{n+1}(t)$ is the position of vehicle $(n+1)$ at the time t. $s(t)$ is the space headway between vehicles at time t. T_r is driver's reaction time, which is called delay time or relaxation time. Vehicle $(n+1)$ travels d_1 distance in the reaction time T_r. d_2 is braking distance of vehicle $(n+1)$. d_3 is braking distance of vehicle n. L is a safe stop distance.

As can be seen from Figure 3,

$$s(t) = x_n(t) - x_{n+1}(t) = d_1 + d_2 - d_3 + L, \tag{2}$$

$$d_1 = T_r \cdot u_{n+1}(t) = T_r \cdot u_{n+1}(t+T_r) = T_r \cdot x'_{n+1}(t). \tag{3}$$

Formula (2) can be rewritten as

$$\begin{gathered} s(t) = x_n(t) - x_{n+1}(t) = d_1 + L + W, \\ W = w_1 + w_2 = d_2 - d_3. \end{gathered} \tag{4}$$

W is a function about the proportion of the car, time t, road geometry features, and weather, which considered vehicle type difference, road conditions, weather conditions, and other factors. They are traffic characteristics items.

w_1 is viscous properties factor.

w_2 is compression properties factor.

Detailed definitions are formulas (10) and (11).

After above derivation transformation, formula (4) can be rewritten as

$$\begin{gathered} x''_{n+1}(t+T_r) = \lambda\left[x'_n(t) - x'_{n+1}(t)\right] - \lambda W' \\ n = 1,2,3,\ldots, \\ \lambda = \frac{1}{T_r}. \end{gathered} \tag{5}$$

It can be seen from formula (5) that vehicle traveling state is affected not only by speed difference between adjacent vehicles but also traffic flow composition, road, weather, and other factors. The latter in formula (5) is a traffic characteristics item.

Jiang et al. model thinks that the relative speed of two vehicles should be considered; that model evolved into [48]

$$x''_{n+1}(t+T_r) = \lambda\left[U(\Delta x) - u_{n+1}(t)\right] + \kappa\Delta u. \tag{6}$$

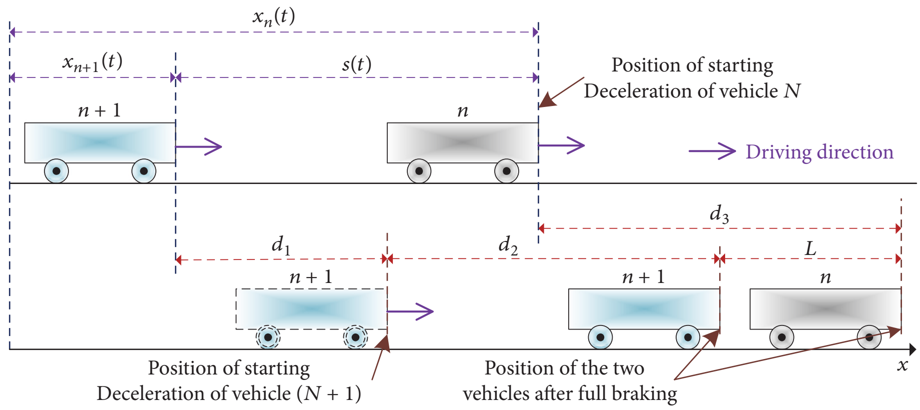


FIGURE 3: Car-following model diagram.

So formulas (5) and (6) could be expressed as follows:

$$x''_{n+1}(t+T_r) = \lambda [U(\Delta x) - u_{n+1}(t)] + \kappa \Delta u - \lambda W',$$
$$W' = w'_1 + w'_2,$$
$$\Delta u = u_n(t) - u_{n+1}(t),$$
$$\Delta x = x_n(t) - x_{n+1}(t). \quad (7)$$

Among them, u_n is speed of vehicle n. u_{n+1} is speed of following vehicle $(n+1)$. λ is response coefficient and κ is reaction coefficient. x_n and x_{n+1}, respectively, are the position of vehicle n and the following vehicle $(n+1)$. U is the function of Δx, while Δx is displacement difference between front and following vehicles.

By converting the microscopic parameters into macroscopic parameters:

$$u_{n+1}(t) : u(x,t),$$
$$u_n(t) : u(x+\Delta x, t),$$
$$U(\Delta x) : u_e(k),$$
$$\lambda = \frac{1}{T_r},$$
$$\kappa = \frac{1}{\tau}. \quad (8)$$

T_r, as described above, is driver's reaction time, which is called delay time or relaxation time. It takes time τ when disturbance propagates backwards the distance Δx.

Make $\lambda W' = \delta_{w1} + \delta_{w2}$; then

$$\frac{du(x,t)}{dt} = \frac{u_e(k) - u(x,t)}{T_r} + \frac{u(x+\Delta x,t) - u(x,t)}{\tau} - (\delta_{w1} + \delta_{w2}), \quad (9)$$

$$\delta_{w1} = \mu \cdot k \cdot \Delta u \cdot u \cdot \frac{S_z}{S_j}, \quad (10)$$

$$\delta_{w2} = \alpha \cdot k \cdot \Delta u \cdot u \cdot \frac{S_z}{S_j}, \quad (11)$$

$$\Delta u = u_i - u_{i+1} \begin{cases} \Delta u, & \Delta u > 0, \\ 0, & \Delta u = 0 \text{ or } \Delta u = \varepsilon, \\ 0, & \Delta u < 0. \end{cases} \quad (12)$$

μ is coefficient of viscosity, its unit is m/(veh·s), which varies with the proportion of the car, and generally its value is in line with the normal distribution [49].

α is the compression coefficient.

u is vehicle speed.

S_z is braking distance of vehicle; the unit is m.

S_j is line of sight; the unit is m.

The left side of (9) is written as a fully differential form, the Taylor expansion on its right, ignoring the high-order terms; then

$$\frac{du(x,t)}{dt} = \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = \frac{u_e(k) - u(x,t)}{T_r} + \frac{\Delta x}{\tau}\frac{\partial u}{\partial x} - \delta_{w1} - \delta_{w2}. \quad (13)$$

In formula (13), $\Delta x/\tau = -ku'_e(k) \equiv a(k) > 0$; it is also called the speed of sound.

Substituting (10) and (11) into (13), at the same time, the conservation of traffic flow should still be satisfied. Then, macroscopic traffic flow model of multiresolution simulation model combined with viscous and compression properties can be collectively represented as follows:

$$\frac{du(x,t)}{dt} = \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = \frac{u_e(k) - u(x,t)}{T_r} + \frac{\Delta x}{\tau}\frac{\partial u}{\partial x} - \mu \cdot k \cdot \Delta u \cdot u \cdot \frac{S_z}{S_j} - \alpha \cdot k \cdot \Delta u \cdot u \cdot \frac{S_z}{S_j}, \tag{14}$$

$$\frac{\partial k}{\partial t} + \frac{\partial q}{\partial x} = g(x,t). \tag{15}$$

k is traffic density. q is traffic volume. x and t, respectively, represent space and time. $g(x,t)$ is source-sink item, which means input or output volume. u is average velocity of traffic flow. $u_e(k)$ expresses the relationship between u and k under the equilibrium state.

5. Mesoscopic Traffic Flow Model

5.1. Hypothesis of Mesomodel. (1) Assume an approximate solution, which is expressed as a linear combination of a set of (formally) simple functions ψ_i and the coefficient of the linear combination is a set of undetermined coefficient C_i.

(2) Considering differential equations and boundary conditions, an objective function F is established to account for the difference between true solution φ and approximate solution $\overline{\varphi}$.

(3) The objective function is minimized by a suitable algorithm—the process of minimization determines the undetermined coefficient, and thus the approximate solution of the problem is achieved.

5.2. The Derivation of Mesomodel. The control equations of the anisotropic kinetic model can be expressed as follows:

$$\frac{du}{dt} = \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = F(k,u)\frac{\partial u}{\partial x} + H \cdot \frac{u_e - u}{T_r} + G(k,u). \tag{16}$$

$F(k,u)$ is velocity gradient coefficient in relaxation term. H is expected term coefficient of the equation. $G(k,u)$ is equation viscous term or nonhomogeneous term.

According to (13), (15), and (16), we can get the following equation:

$$G(k,u) = -\delta_{w1} - \delta_{w2}, \tag{17}$$

$$F(k,u) = \frac{\Delta x}{\tau}, \tag{18}$$

$$H = 1. \tag{19}$$

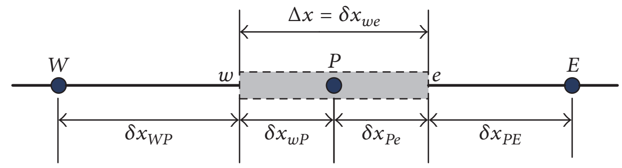


FIGURE 4: Traffic flow control volume diagram.

According to Figure 4 Traffic flow control volume diagram, within a control volume, is integral to (15) during intervals time from t to $(t + \Delta t)$:

$$\int_t^{t+\Delta t}\int_{\Delta v}\frac{\partial k}{\partial t}dv\,dt + \int_t^{t+\Delta t}\int_{\Delta v}\frac{\partial q}{\partial x}dv\,dt = \int_t^{t+\Delta t}\int_{\Delta v} g(x,t)\,dv\,dt. \tag{20}$$

Then,

$$\int_{\Delta v}\left(\int_t^{t+\Delta t}\frac{\partial k}{\partial t}dt\right)dv + \int_t^{t+\Delta t}\left[(Aq)_e - (Aq)_w\right]dt = \int_t^{t+\Delta t}\overline{g}(x,t)\,\Delta v\,dt. \tag{21}$$

In the formula, A is surface area of control volume. A is 1 at one dimension. Δv is volume of control volume. $\Delta v = A \cdot \Delta x$, in which Δx is length of control volume Δx_{we}. $\overline{g}(x,t)$ is average intensity of source-sink item.

For one-dimensional control volume, intervals time is from t to $(t + \Delta t)$; integrate (16) within the control volume and at the boundary:

$$\int_t^{t+\Delta t}\int_{\Delta v}\frac{\partial u}{\partial t}dv\,dt + \int_t^{t+\Delta t}\int_{\Delta v}u\frac{\partial u}{\partial x}dv\,dt = \int_t^{t+\Delta t}\int_{\Delta v}F(k,u)\frac{\partial u}{\partial x}dv\,dt + \int_t^{t+\Delta t}\int_{\Delta v}\frac{u_e - u}{T_r}dv\,dt + \int_t^{t+\Delta t}\int_{\Delta v}G(k,u)\,dv\,dt. \tag{22}$$

Then,

$$\int_{\Delta v}\left(\int_t^{t+\Delta t}\frac{\partial u}{\partial t}dt\right)dv + \int_t^{t+\Delta t}a\left[(Au)_e - (Au)_w\right]dt = \int_t^{t+\Delta t}F(k,u)\left[(Au)_e - (Au)_w\right]dt + \int_t^{t+\Delta t}\int_{\Delta v}\frac{u_e - u}{T_r}dv\,dt + \int_t^{t+\Delta t}\int_{\Delta v}G(k,u)\,dv\,dt. \tag{23}$$

In the formula, subscripts w and e, respectively, represent the initial and terminal section position of control volume. a is upwind scheme parameter.

Equations (17), (18), (21), and (23) compose mesoscopic traffic flow model, which is established by using Finite Volume method. Mesomodel not only has nature of macroscopic traffic model but also has conservation characteristics of integral equations; in particular, its control parameters may not be continuous. In addition, mesoscopic traffic model of the integral form is more suitable to describe traffic flow that contains real discontinuity. Since the integral equation may be intermittently in any position, which has laid a theoretical foundation for travel behavior research of small vehicles fleet, it can be seen as mesoscopic traffic flow model.

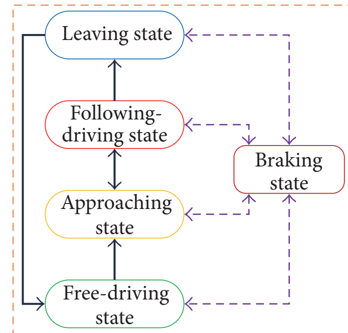


Figure 5: Basic state transition schematic diagram of the car-following driving.

6. Microscopic Traffic Flow Model

Microscopic simulation model of traffic multiresolution model is achieved by using COM methods integrated VISSIM system of German PTV company. VISSIM is a microscopic road traffic modeling tool by simulating traffic operation states to evaluate the program, which takes full account of the traffic characteristics of the motor vehicle, pedestrians, and bicycles. Its core simulation models include ① vehicle longitudinal motion adopted psychophysical car-following model that is put forward by professor Wiedemann of Germany University of Karlsruhe; ② vehicle lateral movement selected Sparmann's model of the lane changing behavior based on psychology and VISSIM used dynamic traffic allocation in path selection [50, 51].

6.1. Wiedemann Conceptual Model Based on Psychological Car-Following Model. Based on the visual psychological hypothesis, Wiedemann et al. proposed a concept model based on driving psychological car-following principle. A basic assumption of Wiedemann model is that the driver adjusts the following speed according to the relative movement between the front and following car, such as the variety of speed and distance. But these stimuli can only be sensed and reacted to by the driver beyond a certain threshold [52, 53]. At the same time, Wiedemann model divides driving status into free-driving state, approaching state, following-driving state, braking state, and leaving state [52, 54].

This paper argues that drivers in following-driving state generally follow these driving patterns: vehicles are usually from free-driving state to approaching state and then into following-driving state and then leaving state, and then become in free-driving state. In these states, there is a possibility that an abrupt state occurs and the vehicle is brought into a braking state. In addition, the approaching state and the following-driving state are often converted into each other. For each driving mode, the acceleration of the rear vehicle is determined by the vehicle speed, speed difference and distance between the front and rear cars, and characteristics of the vehicle. When the driver reaches a certain threshold expressed by the speed difference and distance, he will switch from one driving state to another driving state [50]. Such a change in driving state can be seen in Figure 5.

6.2. The Sparmann Conceptual Model Based on Psychological Lane Changing Rule. The lane changing behavior refers to the behavior of the general vehicle from the current lane to the adjacent lane. The Sparmann lane changing rule is a well-known lane changing model based on psychology [55], whose theoretical basis is the decision-making process model proposed by Willmann for lane changing behavior. Sparmann lane changing process is a typical hierarchical decision; decision-making order of the driver is considered as follows [52]: ① Is there a willingness to change lanes? ② Is driving in the adjacent lane better? ③ Is it feasible to change to the adjacent lane? The specific flow chart is shown in Figure 6.

7. Multiresolution Simulation and Evaluation

7.1. Traffic Simulation Scenario and Parameter Settings. In this paper, "simple simulation scenario" has been established, which is about 2 km from Yan'an East Road interchange to Tianmu Road rotary interchange of North-South Elevated Expressway in Shanghai. Weihai road north entrance ramp and Beijing road south exit ramp are ignored because they are too close to each other. But Xinzha road north entrance ramp is reserved in the simulation scenario. In order to reduce the impact of interchange, the start and end points of simulation scenario have some distance from the interchange of Yan'an East Road and Tianmu Road. Considering the characteristics of the traffic problems, grid cannot be divided too small. In the "simple simulation scenario," the grid is equally divided.

Figure 7 is a schematic diagram of the road model. The left part of Figure 7 is the real road from Yan'an East Road interchange to Tianmu Road rotary interchange. The middle part is the schematic diagram of macroscopic and mesoscopic road model, which identifies road segments and detector locations. The right part of Figure 7 is grid partitioning schematic diagram simulated traffic flow from south to north. Microscopic simulation model is established by VISSIM. Intersection between trunk road (simplified to a single lane) and ramp in grid partitioning schematic diagram corresponds to sections 8 of macroscopic and mesoscopic model. Arrow of sections 8 represents input volume, which actually shows Xinzha road north entrance ramp. To optimize the parameters, simulation test program is designed by using

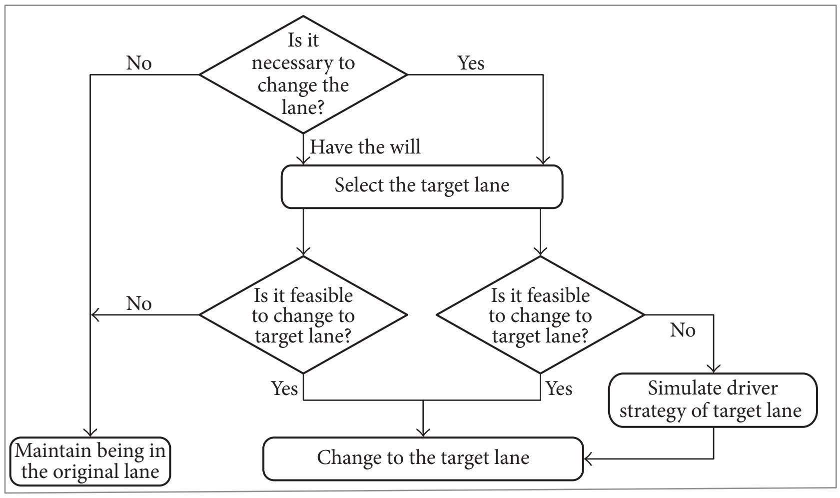


Figure 6: Schematic diagram of changing lane decision-making process.

Table 3: Ramp name, ID, and detector information table of part of North-South Elevated Road.

Link ID	Length of the link (m)	Ramp ID	Ramp name	Detector ID
7	595	Entrance ramp 7 Entrance ramp 8 Exit ramp 7 Exit ramp 8	Yan'an East Road Interchange left turn from west to north Yan'an East Road Interchange right turn from east to north Left turn-Yan'an elevated Right-Yan'an elevated	DX08 DX09
8	595	—	—	DX10
9	565	Entrance ramp 9 Exit ramp 10	Entrance ramp on the north of Weihai road Exit ramp on the south of Beijing road	DX11
10	565	—	—	DX12
11	552	Entrance ramp 11	Entrance ramp on the north of Xinzha road	DX13 DX14
12	552	Entrance ramp 12 Entrance ramp 13 Exit ramp 12 Exit ramp 13	Entrance ramp on the west of Tianmu Road rotary interchange Entrance ramp on the east of Tianmu Road rotary interchange Exit ramp on the west of Tianmu Road rotary interchange Exit ramp on the east of Tianmu road rotary interchange	DX15

Latin orthogonal test method in the simulation scenario. This figure is not drawn to scale for clarity of presentation.

In this paper, the actual test data is used, September 22, 2009 detector data, and sampling frequency is 1 minute. Table 3 shows the Ramp ID, Name, and Detector ID. Research scenario is part of North-South Elevated Road and detector IDs are from DX08 to DX15.

In this paper, upwind scheme is used to numerically solve the macromodel and mesomodel. In "simple simulation scenario," parameter initial values of the macroscopic and mesoscopic model are set as follows:

Free-flow speed $u_f(x) = \{21, 21, 21, 21, 21, 21, 21, 21, 21, 21\}$ m/s.

Jam density $k_j(x) = \{0.16, 0.16, 0.16, 0.16, 0.16, 0.16, 0.16, 0.16, 0.16, 0.16\}$ veh/m.

Initial density $k(i) = \{0.035, 1 \le i \le 5; 0.12, 6 \le i \le 7; 0.014, 8 \le i \le 10\}$ (unit is veh/m).

Input volume constant $Q_{\text{in}} = \{0.12, 0.12, 0.24, 0.24, 0.24, 0.48, 0.12, 0.12, 0.12, 0.12\}$ (unit is veh/s).

Output volume constant $Q_{\text{out,val}} = 0.16$ (unit is veh/s); output volume $Q_{\text{out}} = (k_{10}u(k_{10}), Q_{\text{out,val}})$.

Simulation step $t = 1$ s. T is 300 simulation steps. Link length L is 2000 m. Grid is equally divided and length of each grid is 200 m. Input volume, S8, of macromodel is 0.48 veh/s, while input volume, S8, of mesomodel is 0.44 veh/s. In the micromodel, parameters include the following. Free-flow speed of section is 80 km/h. Traffic capacity of expressway and ramp are, respectively, 2400 veh/h and 1200 veh/h.

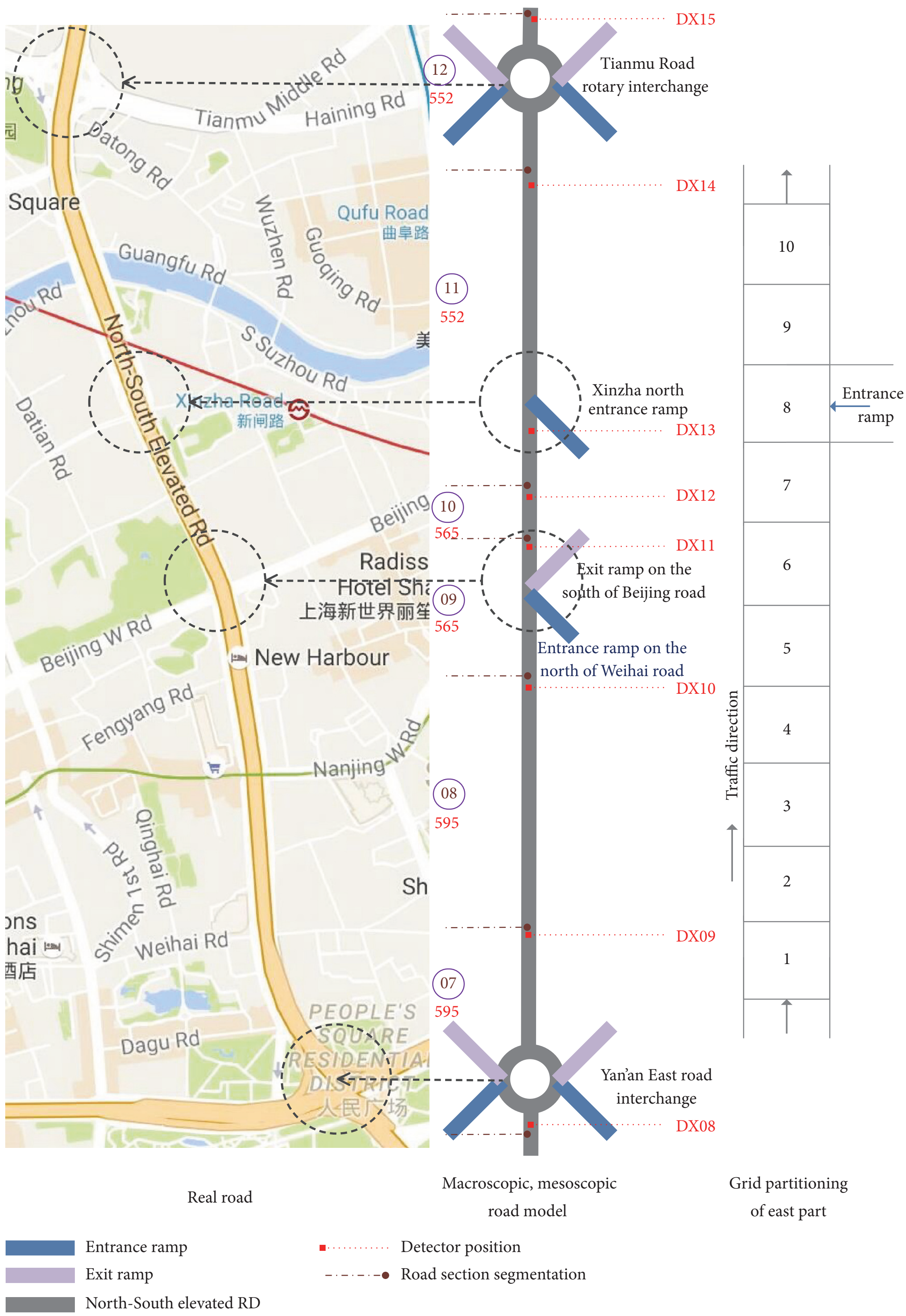


FIGURE 7: Basic road schematic diagram of multiresolution traffic simulation model.

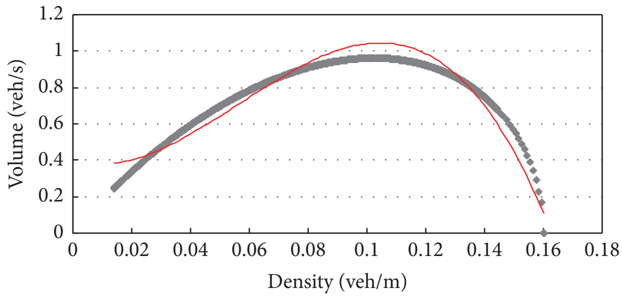


Figure 8: Volume-density relationship diagram of macromodel.

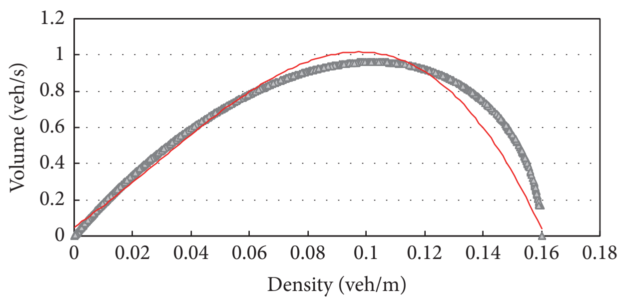


Figure 9: Volume-density relationship diagram of mesomodel.

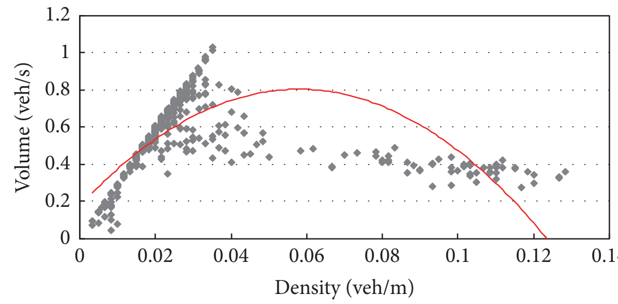


Figure 10: Volume-density relationship diagram of micromodel.

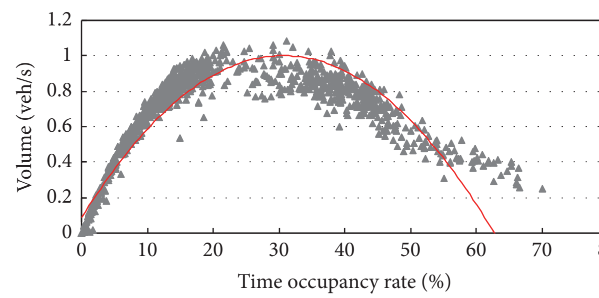


Figure 11: Volume-time occupancy rate relationship graph of detector data.

7.2. Volume Consistency Analysis of Multiresolution Model

7.2.1. Consistency Analysis of Road Section Volume-Density Relationship. Figures 8, 9, and 10, are, respectively, the volume-density relationship diagram of macromodel, mesomodel, and micromodel. Figure 11 is a volume-time occupancy rate relationship graph of detector data. The grey points are simulation data and red line is polynomial trend line of data.

As can be seen from the figure, oscillation of data points and trend line in the volume-density diagram of macromodel and mesomodel are small. The whole trend line is shaped as a parabolic, the maximum volume in trend line is about 1 veh/s, and jam density is about 0.16 veh/m. Data of volume-density diagram of micromodel distributed around the trend line and the whole trend line is shaped as a parabolic, but oscillation of data is bigger. Simultaneously, the maximum volume in micromodel trend line is about 0.8 veh/s and jam density is about 0.125 veh/m. Data in volume-time occupancy rate relationship graph of detector data distributed around the trend line, the whole trend line is shaped as a parabolic, and oscillation of data is small. The maximum volume in trend line of actual detector data is about 1 veh/s and its time occupancy ratio in traffic jam state is about 63%.

From a qualitative point of view, volume-density relationships of macroscopic, mesoscopic, and microscopic models are unanimous with detector data. Among them, fluctuations of simulation data of macromodel and mesomodel are relatively smaller and their consistencies are relatively higher. However, fluctuation of simulation data of micromodel is relatively bigger and its consistency is relatively lower. Maybe it is because of that fact that micromodel's description is more detailed and its randomness among vehicles is bigger.

7.2.2. Volume Error Analysis of Different Models. In order to quantitatively evaluate the validity and applicability of multiresolution transport model, the following several indicators are used: Mean Absolute Error (MAE), Relative Error (RE), Mean square Error (MSE), and Standard Deviation (St.D). For RE, the result considers the effect of "maximum relative error" and "gross error" has been processed according to Dixon guidelines [56]. Table 4 is the volume analysis of each model. In order to comparatively analyze several models, Cell Transmission Model (CTM) is as a reference model.

$$\begin{aligned} \text{MAE} &= \frac{\left(\sum_1^n \left|\text{true value} - \text{prediction value}\right|\right)}{n}, \\ \text{RE} &= \frac{\left(\sum_1^n \left(\left(\left|\text{true value} - \text{prediction value}\right|\right)/\text{true value}\right)\right)}{n}, \\ \text{MSE} &= \frac{\left(\sum_1^n \left(\text{true value} - \text{prediction value}\right)^2\right)}{n}, \\ \text{St.D} &= \left(\frac{\left(\sum_1^n \left(\text{true value} - \text{prediction value}\right)^2\right)}{(n-1)}\right)^{1/2}. \end{aligned} \tag{24}$$

When the traffic flow density is higher, MAE of mesomodel is the biggest one, macromodel's MAE is the smallest one, MAE of CTM and micromodel are in the between. Considering RE, Relative Error of macromodel is the smallest, its value of CTM is the biggest one, RE of mesomodel and

Table 4: Volume analysis of each model.

Model	Average density (veh/m)	MAE	RE	MSE	St.D
CTM	0.1154	0.24	0.25	0.09	0.29
Macromodel	0.1225	0.21	0.20	0.08	0.28
Mesomodel	0.1250	0.31	0.24	0.15	0.39
Micromodel	0.1033	0.26	0.23	0.13	0.36

micromodel are close, which are in between the minimum and maximum. Considering MSE and St.D, the values of macromodel and CTM are close, which are smaller. However, MSE and St.D of mesomodel and micromodel are close, which are bigger.

It can be seen, when the traffic density is high, because macromodel takes into account viscous and compression properties, that the simulation result of macromodel has a high precision, the error is small, and the dispersion of results is smaller. Micromodel can reflect the characteristics of individual vehicles, its error is larger, and its dispersion of simulation results is bigger; because randomness of micromodel is relatively large, time offset and position offset are high. The situation is more significant when traffic volume is small and its density is low. Considering mesomodel, it can combine partial characteristics of macromodel and micromodel, compared with CTM; their RE values have 4% differences. But mesomodel can reflect some random nature of traffic, which leads to its MSE and St.D being larger than CTM. Compared with micromodel, mesomodel greatly improves the simulation efficiency and application scope. Compared with macromodel, simulation accuracy of microscopic and mesoscopic model are lower but errors are bigger, because of random nature and its time offset and location offset in statistical analysis.

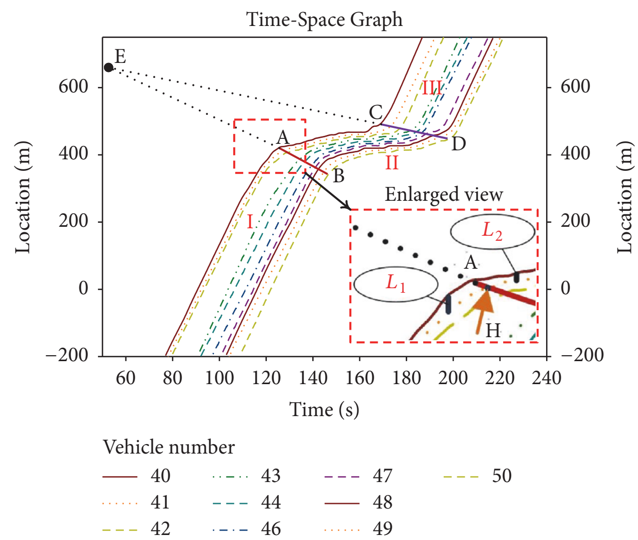


Figure 12: Vehicle time-space trajectories diagram of micromodel.

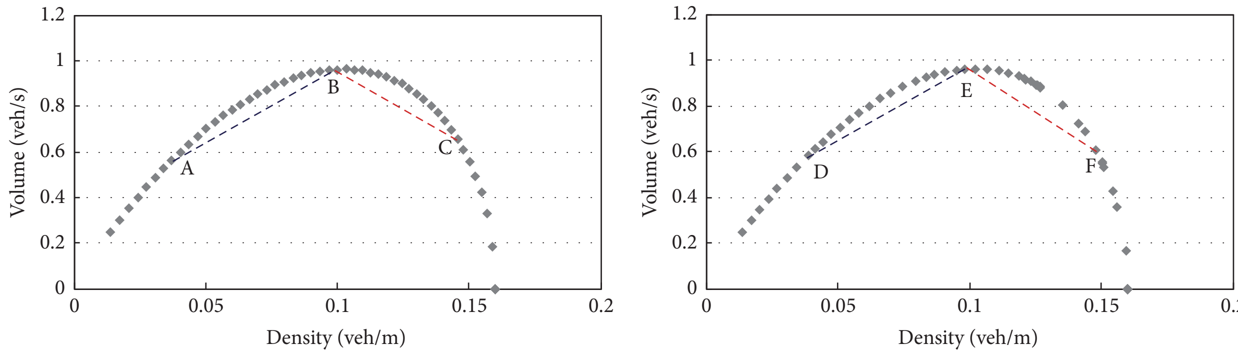
7.3. Consistency Analysis of Multiresolution Model

7.3.1. Traffic Wave Analysis of Microscopic Model. The paper compares each submodel of multiresolution model based on the same real scenario to evaluate consistency of multiresolution model, which is expressed by consistency analysis of traffic wave. Figure 12 is vehicle time-space trajectories diagram of micromodel, which can analyze traffic state transition process in microscopic simulation. Traffic waves verification data correspond to grids 6–10 of macroscopic and mesoscopic model in the paper. In Figure 12, horizontal axis is simulation time (second), while the actual time is simulation time multiplied by simulation speed coefficient; vertical axis represents location of the vehicle (meter). Each curve represents time-space trajectories of each vehicle. Horizontal distance of curves indicates time headway; vertical distance represents space headway. Solid lines AB and CD represent distributed wave, which reflects a shift interface of density state; slope of solid line is wave velocity; positive and negative slope, respectively, represent a forward or backward characteristic of fluctuations.

7.3.2. Traffic Wave Analysis of Macroscopic and Mesoscopic Model. (a) and (b) in Figure 13, respectively, are grid 8 traffic volume-density relationship of macromodel and mesomodel. In the volume-density relationship curve, velocity of distributed wave is slope of secant line, such as secants AB, BC, DE, and EF; velocity of weak wave is the slope of the tangent. Moreover, in the range of free flow, the fluctuation velocity is positive; namely, wave propagation direction is the same with the traveling direction of traffic flow. But in the range of jam traffic flow, the fluctuation velocity is negative; namely, wave propagation direction is the converse of the traveling direction of traffic flow.

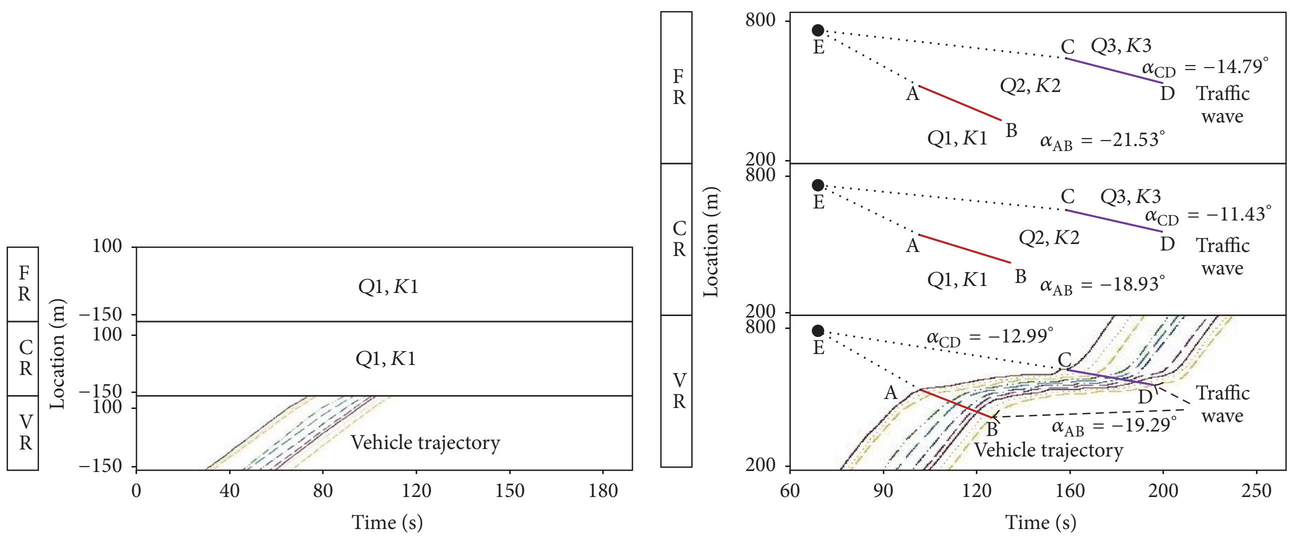
When the traffic flow low-density and low volume state, A (D), transform to the higher density higher volume state, B (E), the velocity of distributed wave is positive and its propagation direction is along the road. When the traffic flow high-density and low volume state, C (F), transform to the lower density higher volume state, B (E), the velocity of distributed wave is negative and its propagation direction is back along the road. The wave from the state A (D) to the state B (E) is concentrated wave, and the wave from the state B (E) to the state A (D) is evanescent wave, both of which are progressive waves. The wave from the state C (F) to the state B (E) is evanescent wave, and the wave from the state B (E) to the state C (F) is concentrated wave, both of which are retrograde waves.

7.3.3. Traffic Wave Consistency Analysis of Multiresolution Model. Figure 14 is traffic wave consistency analysis of multiresolution model, and Figure 14(a) shows transportation



(a) Macromodel (b) Mesomodel

Figure 13: Grid 8 traffic volume-density relationship diagram.



(a) (b)

Figure 14: Traffic wave consistency analysis schematic diagram of multiresolution model.

performance when free moving. That is to say, the transportation is free moving during 25~100 simulation seconds at road section −150~100 m. Meanwhile, time-space trajectories of vehicles are described in micromodel schematic diagram; however, there are no curves in macroscopic and mesoscopic model schematic diagram. As shown in the figure, traffic keeps in state Q_1, K_1 without changing during the period at this section.

Figure 14(b) is the schematic diagram of traffic wave consistency analysis of multiresolution model. It shows the traffic operating status when the traffic density changes, which describes the traffic state transition process from concentrated wave to evanescent wave during 60~250 s at road section 200~800 m. In micromodel results, it describes time-space trajectories of vehicles and concentrated wave AB and evanescent wave CD. In macromodel and mesomodel results, they describe the curves of traffic waves with respect to the micromodel waves. As shown in Figure 14, the area is divided into three traffic states according to solid lines AB and CD and the extended line, which includes Q_1, K_1, Q_2, K_2, Q_3, K_3. Boundaries AB and CD represent thresholds of the traffic state transition, and the solid line AB represents the concentrate wave, which reflects the phenomenon of traffic state transition boundaries from the low-density to the high-density. Simultaneously, the wave is retrograde wave, while the solid line CD represents the evanescent wave, which reflects the phenomenon of traffic state transition boundaries from the high-density to the low-density. Simultaneously, the wave is retrograde wave. In addition, depending on the angle between the lines AB and CD, we can know that the values of wave velocity of different models are different.

7.3.4. Traffic Wave Consistency Error Analysis of Multiresolution Model. Traffic wave qualitative analyses of different models have been studied above; traffic wave quantitative analyses will be discussed in the following, using MAE, RE, MSE, and St.D indexes. Table 5 is grid 8 traffic wave velocity Error Analysis of multiresolution model. About the traffic wave velocity, positive sign in the table represents the forward propagation wave; negative sign indicates backward

Table 5: Grid 8 traffic wave velocity Error Analysis of multiresolution model.

Model	Wave number	Wave velocity (m/s)	Angle (degree)	Index			
				MAE	RE	MSE	St.D
Macromodel	Wave AB	−3.95	−21.53	0.4858	0.1404	0.2360	0.4858
	Wave CD	−2.64	−14.79	0.0825	0.0323	0.0068	0.0825
	Mean value	—	—	0.2841	0.0863	0.1214	0.2841
Mesomodel	Wave AB	−3.43	−18.93	0.0303	0.0088	0.0009	0.0303
	Wave CD	−2.02	−11.43	0.5359	0.2096	0.2872	0.5359
	Mean value	—	—	0.2831	0.1092	0.1441	0.2831
CTM	Wave AB	−2.96	−16.51	0.4954	0.1432	0.2455	0.4954
	Wave CD	−3.26	−18.06	0.7030	0.2749	0.4942	0.7030
	Mean value	—	—	0.5992	0.2091	0.3698	0.5992
Micromodel	Wave AB	−3.50	−19.29	0.0400	0.0116	0.0016	0.0400
	Wave CD	−2.31	−12.99	0.2495	0.0976	0.0623	0.2495
	Mean value	—	—	0.1448	0.0546	0.0319	0.1448

propagation wave. Corresponding angle of wave velocity can be found in Figure 14. In the table, the wave velocity values correspond to the result based on time consistency, spatial consistency, and interface consistency of each model. Speed and solving process of wave velocity in microscopic model have considered the simulation accuracy parameter impact of VISSIM. Simulation accuracy is 10 time steps per simulation seconds here. Error Analysis in Table 5 is based on the mean of all model simulation results.

As shown in Table 5, for traffic wave of each model, RE of macromodel and micromodel are close, both of which are at a lower level; RE of CTM is bigger and RE of mesomodel is between them. For evaluation index MSE, MSE of microscopic model is in lower level; MSE of CTM is relatively larger, and MSE of macromodel and its value of mesomodel are in between.

As can be seen, these four models can simulate changes of traffic state, capture traffic wave, and have higher simulation accuracy, wherein micromodel's simulation accuracy is the highest and result's dispersion degree is the lowest, thanks to the micromodels' sophisticated simulation capabilities. The macromodel simulation accuracy is relatively higher because of the detailed description of traffic impedance (viscous and compression properties). The mesomodel simulation accuracy is higher than CTM and is lower than macromodel. Compared with CTM, mesomodel considers dynamics of traffic and can describe traffic state transition process more delicately than CTM. Compared with macromodel, mesomodel can describe a certain discrete stochastic state, but it also resulted in low accuracy and higher dispersion degree.

Meanwhile, the simulation results of different resolution models can have differences because of the time offset, position offset, inconsistency of interface, and control parameters. In order to obtain better results, they can be achieved by parameter optimization of different models, including unified interface and consistent optimization of time and space.

8. Conclusion

By comparing the characteristics of single resolution model, the paper has determined the multiresolution technology to study the traffic flow model of urban expressway main line and its ramp. Firstly, the idea of multiresolution modeling is expounded and the multiresolution traffic simulation triangular frame is constructed by using the integrated simulation method. Secondly, integration strategy issues, the key problem of multiresolution traffic simulation, are elaborated. The paper proposes a novel multiresolution traffic simulation model by asynchronous integration strategy based on Set Theory, which can describe the characteristics of traffic system, such as behavioral characteristics, time characteristics, spatial characteristics, performance characteristics, granularity level, and internal structure. Then, according to the characteristics of urban expressway traffic flow and macromodel goal, the conceptual model and mathematical model of macroscopic traffic flow, combining viscosity characteristic and compression characteristic, are established in detail. Meanwhile, based on the macroscopic traffic flow model, a new mesoscopic traffic flow model is established by using the weighted residual method and the finite difference method. Moreover, the microscopic model is discussed by using VISSIM of German PTV company. In addition, in order to simulate and evaluate the multiresolution model, the paper established "simple simulation scenario," which is about 2 km from Yan'an East Road interchange to Tianmu Road rotary interchange of North-South Elevated Expressway in Shanghai. Finally, simulation results of multiresolution model have been analyzed from several aspects, volume consistency, traffic wave consistency, and Error Analysis, and so on. The paper used MAE, RE, MSE, and St.D to quantitatively evaluate the validity and applicability of multiresolution transport model. The results show that the novel multiresolution model can simulate characteristics of traffic flow and keep the consistency of traffic state transition. It can capture traffic wave and have higher simulation accuracy. And it is feasible and effective in traffic simulation.

Conflicts of Interest

The authors declare that they have no financial and personal relationships with other people or organizations that can inappropriately influence their work; there is no professional or other personal interest of any nature or kind in any product, service, or company that could be construed as influencing the position presented in, or the review of, the manuscript.

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