Application of Simulation-based Dynamic Traffic Model on Freeway Network: A Case Study of Jiangsu Province in China

Submitted by

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ABSTRACT

An analytical tool with high time resolution is necessary for the traffic operation management of freeway network. This paper proposes the application of simulation-based dynamic traffic model on freeway network. The total length of the analyzed freeway network in Jiangsu province is 4246km, and there are around 1 million vehicles per day. The model can represent the time-dependent traffic condition of the whole network, and evaluate operation management strategies in large scale area which cannot be accomplished by macro four-step transportation model or micro traffic simulation model. The model is implemented by DTALite and the process of model building including data quality control, demand and supply preparation, and model validity checking. Freeway toll records and traffic count data are utilized to validate the model results on three levels: network, OD pairs and links. At last, the work zone scenario test is conducted by the validated model. The validation results indicate the dynamic traffic model can represent the time-dependent traffic condition with high accuracy, and the results of the scenario test show that the model can evaluate different operation management strategies quantitatively and reliability.

Key Words: Freeway Traffic Operation and Management, Dynamic Traffic Model, Simulation-based Method, DTALite
1 INTRODUCTION

Freeway network is the important support and guarantee of the regional economy and social businesses. When making the traffic operation management strategy in China, traffic count data and video monitors are applied to evaluate the traffic condition, and then the strategies are proposed based on the existing traffic problem. However, there are several obstacles in this process. First, it is difficult to have an overview of the traffic condition of the whole freeway network due to the limited available detecting equipment. Nowadays, the detecting equipment can only cover parts of critical links and this leads to the evaluation of traffic condition merely focusing on individual segments but cannot analyze the temporal and spatial traffic condition of the whole network which is important to understand the formation and dissipation of traffic congestion. Moreover, although the freeway administrators can make the traffic operation management strategies based on their experience, they cannot guarantee the implementation effect without the beforehand evaluation, and the desired effect of the strategies always cannot be achieved. The deficiency of traffic data collection and the lack of suitable analytical tools are the key problems of freeway traffic operation management in China. Traffic simulation model can represent the traffic condition of the network with appropriate input data and it provides the possibility to solve the above problems. However, the macro four-step transportation model only can represent the average traffic condition of the analyzing time period while cannot show the evolution process on time dimension, which is particularly important for traffic operation management. Micro traffic simulation model can represent the temporal variation of traffic condition. Nevertheless, its shortages on computational efficiency and route choice function determine that the micro traffic simulation model is difficult to apply to high volume and large scale freeway network.

Dynamic traffic model can cover the deficiency of macro four-step transportation model and micro traffic simulation model when applying on traffic operation management of freeway network. In dynamic traffic model, time-dependent travel demands are successively loaded onto the freeway network; dynamic route choice (i.e. DRC) function can simulate the travelers’ route choice behavior and dynamic network loading (i.e. DNL) function can represent the propagation process of traffic flow. The combination of DRC and DNL is called dynamic traffic assignment (DTA) (1). Dynamic traffic model can indicate the time-dependent traffic condition of the entire freeway network; meanwhile, its computation efficiency is between macro four-step transportation model and micro traffic simulation model, and can handle the high volume of freeway network.

Dynamic traffic model can be categorized by analytical model and simulation-based model. Comparing with analytical model, simulation-based model are more appropriate for the actual and large scale traffic network (2). Nowadays, there are several successful applications of dynamic traffic model on practical networks. DynaMIT was utilized to simulate the time dependent traffic condition on Hampton roads, Virginia (3). Partial urban network of Jinan, China, applied DynaCHINA to estimate and predict the traffic condition (4). A dynamic traffic model was established by TRANSIMS and it was used in simulating the traffic condition under emergency evacuation around the central part of Chicago (5). Washington D.C. also used TRANSIMS to evaluate the traffic congestion degree around the area of the white house after closing several streets (6). Transportation Research and Modeling Services (TRMS) used DynusT to establish the dynamic traffic model for Portland Metropolitan Region (7). The model were applied to analyze the traffic congestion during the peak hour and evaluate the operation management strategies. North Carolina applied DynusT and DTALite to analyze the traffic impact of the work zones on I-40 and I-440 (8). The model not only represented the traffic condition of the related regional network, but also considered the travel demand at the regional level.
network, but also evaluated the traffic organization plan. National Center for Smart Growth (NCSG) used TRANSIMS and DTALite separately to build the dynamic traffic model for the entire Maryland State based on the existing static model named Maryland Statewide Transportation Model (9, 10). The dynamic traffic model was applied to analyze the time-dependent traffic condition in the future.

Time-dependent OD (TDOD) reflects the time variation of travel demand and the accuracy of TDOD directly affects the reliability of model results. Freeway network tolling system in China automatically collects the toll record of each vehicle that entering the freeway network. The toll record includes the vehicle type, enter/exit toll station, enter/exit time, etc. These toll records are integrity, consistency and accurate (11). After data quality control, freeway toll records can transfer to actual TDOD which is more reliable than the estimated ones.

In order to improve the analytical ability of the time-dependent traffic condition of the entire freeway network by using the existing traffic information, Jiangsu Freeway Network Operation & Management Center asked Tongji University to test whether the dynamic traffic model can meet the application requirements. In this study, the dynamic traffic model is implemented using DTALite. The travel demand has been split into 15min interval based on freeway toll records. The whole freeway network (total length is 4246km) of Jiangsu province has been built in this model, including 316 toll stations, 1113 nodes and 2282 single direction links. The daily volume is around 1,000,000 vehicles per day. The validation of model results indicates that the freeway dynamic traffic model can represent the time-dependent traffic condition of the entire network in high accuracy. It also enable the evaluation of different traffic operation management strategies.

The paper is organized as follows: Section 2 describes the process of simulation-based dynamic traffic model; Section 3 gives an overview of the establishment of dynamic traffic model; Section 4 shows the model validation on three different levels: network, OD and link; Section 5 presents the application on work zone operation management by scenario test; Section 6 is the conclusion about this study.

2 PROCESS OF SIMULATION-BASED DYNAMIC TRAFFIC MODEL

2.1 Model Approach

There are mainly three different criteria of dynamic route choice behavior: Dynamic System Optimum (DSO), Dynamic User Equilibrium (DUE) and Reactive Route Choice (RRC) (12). When the traffic condition reaches DSO, the total experienced travel times (generalized cost) of all the OD pairs are the lowest. DSO always applies to theoretical research on experimental network and emergency evacuation on real network. DUE is the most widely used criterion and the definition is “in a network with many O-D zones and in a specific time period, for each O-D pair and departure time increment, all used routes have equal and lowest experienced travel time (generalized cost) and no user may lower their experienced travel time (generalized cost) through unilateral act (generalized cost) and no user may lower their experienced travel time (generalized cost)” (13). DUE is generally used to represent the daily traffic condition. DSO and DUE both need iterative computations and they choose the shortest route based on experienced travel time. RRC is different from DSO and DUE. When travelers follow RRC, they choose the shortest route based on instantaneous travel time. RRC always applies to simulate the route choice behavior when travelers receive real-time traffic guidance information and it needs no iteration.

In this study, we used DUE to represent the daily traffic condition, and use RRC to describe the route choice behavior when travelers receive traffic guidance information from variable message sign (VMS). The processes of simulation-based dynamic traffic model based on DUE...
and RRC are presented respectively in FIGURE 1 (a) and (b).

**FIGURE 1 Process of Dynamic Traffic Model**

DUE and RRC are usually combined to represent the actual traffic condition in practice. Take work zone as an example. When there is no work zone, all the travelers follow DUE and mark the route choice results as “E”; when the work zone exists on the first day and there is no information about it, the travelers do not know the work zone exists until they arrive at the work zone location, so all the travelers will still use the route choice “E”; when the work zone exists on the first day and the traffic guidance information system works, some travelers that receive the information will consider if they should change their routes. No matter whether these travelers change their routes or not, their route choice decisions now are based on the instantaneous travel time, so they belongs to RRC and set their route choice results as “R”. In this situation, the travelers are divided into two parts: one part follows DUE and the other part follows RRC, and the model building needs the combination of iterative DUE and non-iterative RRC.
2.2 Convergence Criterion

Relative Gap (RG) are always used as the convergence criterion of DUE, the definition of RG is as follows (13):

\[
\begin{align*}
\gap = & \sum_{u \in U, p \in P, m \in M, d \in D} \left( q_{\text{PATH}(m,d,k,p)}^u \tau_{(m,d,p,k)}^u - \sum_{u \in U, p \in P, m \in M, d \in D} q_{\text{OD}(m,d,p)}^u \omega_{\text{min}(m,d,p)}^u \right) \\
& \sum_{u \in U, p \in P, m \in M, d \in D} q_{\text{OD}(m,d,p)}^u \omega_{\text{min}(m,d,p)}^u
\end{align*}
\]

Where \( U \) is the set of vehicle type \( u \); \( P \) is the set of time period \( p \); \( M \) is the set of origin toll station \( m \); \( D \) is the set of destination toll station \( d \); \( K_{(m,d,p)} \) is the set of route \( k \) from toll station \( m \) to toll station \( d \) during time period \( p \); \( q_{\text{PATH}(m,d,k,p)}^u \) is the volume of vehicle type \( u \) from toll station \( m \) to toll station \( d \) on route \( k \) during time period \( p \); \( \tau_{(m,d,p,k)}^u \) is the travel time of vehicle type \( u \) from toll station \( m \) to toll station \( d \) on route \( k \) during time period \( p \); \( q_{\text{OD}(m,d,p)}^u \) is the volume of vehicle type \( u \) from toll station \( m \) to toll station \( d \) during time period \( p \); \( \omega_{\text{min}(m,d,p)}^u \) is the shortest travel time of vehicle type \( u \) from toll station \( m \) to toll station \( d \) during time period \( p \); \(|\epsilon_{\text{DUE}}| \) is the convergence criterion, and it is normally set as 5%.

3 FREEWAY DYNAMIC TRAFFIC MODEL BUILDING

3.1 Freeway Toll Record Quality Control

The study area in this research is Jiangsu province (102,600 km²). The total length of the entire freeway network of Jiangsu province is 4,245 km (2,638 mile) and there are 316 toll stations in 2012. The available toll records cover all the toll stations of July 2012. There are 24,221,231 Manual Toll Collection (MTC) records and 5,631,769 Electronic Toll Collection (ETC) records. Each record contains the information of one trip including vehicle type, entry/exit toll station, and entry/exit time. The entry/exit time is accurate to the second. After aggregating these toll records by entry time, we can get the TDOD in 15 min interval. The time-dependent travel time among different toll stations, which can be used for model validation, also can be calculated by toll records.

However, there are some flawed data in the original toll records including the same entry/exit toll station, abnormal entry/exit time and abnormal travel speed. The same entry/exit toll station means the entry station of one toll record is the same with the exit station. It is usually caused by the u turn at the service area. Abnormal entry/exit time record means the entry time is later than the exit time. It is caused by the time system among different toll stations happens to be unsynchronized. These two kinds of flawed data can be filtered by simple logic judgment.

Abnormal travel speed means the travel speed of one vehicle is out of the normal range. The two-sided test based on standard deviation is applied to identify the abnormal travel speed in different traffic condition. The principle is when the difference between the observed value and the average value in a specified time interval is larger than standard deviation \( X \) times, the observed value is identified as an abnormal data and need to be eliminated. The following is the detail steps.

Step1: Calculate the travel speed of each vehicle from station \( m \) to station \( d \);
Step2: Calculate the average travel speed and standard deviation of each time interval;
Step3: Check each toll record of one time interval in turn. If (travel speed of vehicle \( n \) - average travel speed)/standard deviation\( >X \), mark this toll record as abnormal data and delete it.
Step4: Recalculate the average travel speed and standard deviation of each time interval by the filtered toll record.
Step5: Repeat Step3 to Step4 until there is no more abnormal data.
After quality control, 86.7% toll records are available. In the problematic data, 95.5% belongs to abnormal travel speed, 2.8% belongs to abnormal entry/exit time and 1.7% belongs to the same entry/exit toll station. The problematic data cannot be used for validation. However, the data with abnormal travel speed has accurate entry/exit station and entry time and these data still can be included in the TDOD. The data with abnormal entry/exit time and same entry/exit station only takes 0.6% of the entire travel demand, and the reliability of these data about entry/exit station and entry time cannot be guaranteed, so they should be excluded from the TDOD.

3.2 Demand and Supply Preparation

(1) Time-dependent Travel Demand

The time-dependent OD of each vehicle type in 15min time interval is calculated for the analyzing time period as follows:

\[ V^u_{OD(m,d,p)} = \text{count(freeway toll records)} \]

where \{entry \text{ station}=m \text{ and exit \text{ station}=d \text{ and vehicle type}=u \text{ and entry \text{ time} \in [t_p,t_{p+1}])}\}

Where \( V^u_{OD(m,d,p)} \) means the time-dependent OD volume of vehicle type \( u \) from toll station \( m \) to toll station \( d \) in time period \( p \); \( t_p \) and \( t_{p+1} \) is the start time and end time of time period \( p \). The time requirement is only on entry time. It means when a vehicle enters the freeway in time period \( p \) and no matter when it leaves, this vehicle need to be counted.

There are four types of passenger cars and five types of freight vehicles in the freeway network. Small passenger car (P1) takes the largest part of traffic volume in Jiangsu freeway network and the proportion is 68.6% in July 2012. Each vehicle type has different periodical entry volume distribution (FIGURE 2(b, c)); moreover, the impact of different vehicle types on traffic condition varies due to the various vehicle physical sizes and driving performances. Therefore, it is necessary to upload the time-dependent travel demand of each vehicle type separately. HCM 2010 (14) gives the suggested passenger car equivalent (PCE) of heavy vehicles in the freeway basic segment on the plain topography. Based on HCM 2010 and the different vehicle sizes, the PCE of each vehicle type is shown in FIGURE 2(a). The value of time is applied by existing research (15).

(a) Characteristics of Different Passenger Cars and Freight Vehicles

<table>
<thead>
<tr>
<th>Type ID</th>
<th>Classification Criterion</th>
<th>Vehicle Length (m)</th>
<th>Traffic Volume Proportion (%)</th>
<th>Passenger Car Equivalent (unit 1)</th>
<th>Value of Time (dollar/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>≤7 seats</td>
<td>3.5~6</td>
<td>68.6</td>
<td>1.0</td>
<td>2.15</td>
</tr>
<tr>
<td>P2</td>
<td>8~9 seats</td>
<td>6~9</td>
<td>0.9</td>
<td>1.0</td>
<td>2.19</td>
</tr>
<tr>
<td>P3</td>
<td>20~29 seats</td>
<td>9~12</td>
<td>0.9</td>
<td>1.0</td>
<td>4.73</td>
</tr>
<tr>
<td>P4</td>
<td>≥40 seats</td>
<td>12~13.7</td>
<td>1.3</td>
<td>2.0</td>
<td>4.77</td>
</tr>
<tr>
<td>F1</td>
<td>≤2t</td>
<td>3.5~4.5</td>
<td>6.2</td>
<td>1.2</td>
<td>4.46</td>
</tr>
<tr>
<td>F2</td>
<td>2~5t (include 5t)</td>
<td>4.5~6</td>
<td>9.1</td>
<td>1.5</td>
<td>4.53</td>
</tr>
<tr>
<td>F3</td>
<td>5~10t (include 10t)</td>
<td>6~8</td>
<td>4.1</td>
<td>1.5</td>
<td>6.09</td>
</tr>
<tr>
<td>F4</td>
<td>10~15t (include 15t)</td>
<td>8~12</td>
<td>4.5</td>
<td>2.0</td>
<td>6.29</td>
</tr>
<tr>
<td>F5</td>
<td>&gt;15t</td>
<td>12~16.5</td>
<td>3.3</td>
<td>2.5</td>
<td>6.38</td>
</tr>
</tbody>
</table>
FIGURE 2 Characteristics of Different Vehicle Types in Freeway

(2) Freeway Network

The basic elements of the freeway network include freeway basic link, toll station, interchange ramp and toll station ramp (FIGURE 2 (a)). Freeway basic links connect the adjacent toll stations. The average basic link of Jiangsu freeway network is 9.3km. The DNL model of DTALite is link-based and the smallest analytical unit is the single link. A long link is inappropriate to present the traffic condition well in spatial dimension. Therefore, each freeway basic link has been split equally and the length varied from 0.2km to 5km. The low bound of link length satisfied the Courant-Friedrichs-Levy condition (CFL) condition (16) which means each vehicle in one time step only can traverse one link. The free flow speed of the model is 120km/h (75 mph) and the time step of DNL model is 6s, so a vehicle can drive 0.2km in each time step at most. After splitting, the average link length is 3.2km and the shortest length is 0.35km.

Freeway toll stations work as activity location in dynamic traffic model. All the vehicles enter and exit the freeway network through toll stations. There are two kinds of toll stations: the normal toll station and the mainline toll station. The normal toll station connects with the freeway network by on/off-ramp (FIGURE 3 (c)). The mainline toll station is the beginning or the ending of freeway and connects the network directly. There is always a toll square at the mainline toll station. When
there are many vehicles exiting the mainline toll station at the same time, the square can keep the vehicles for a while so that the congestion will not spread to the freeway basic link immediately. Therefore, the ramp of mainline toll station is still needed to work as the toll square.

Interchange connects two freeways and vehicles can drive from one freeway to the other through the interchange ramp. When there is congestion near an interchange, the congestion may spread to the adjacent freeway through the interchange ramp. Therefore, the interchange ramp (FIGURE 3 (c)) is necessary in consideration of congestion propagation.

The link transmission model in DTALite is based on Daganzo fundamental diagram so the travel speed keeps constant in free flow pattern which means the speed limit equals to the critical speed \( (17) \). Thus, the predetermined traffic flow parameters of DTALite include lane capacity, speed limit and jam density (FIGURE 3 (d)). The shock wave speed can be calculated as Lane Capacity/ [Jam Density-(Lane Capacity/Speed Limit)]. In addition, the capacity of the off-ramp relates with the exit capacity of the toll station. When there are not enough exit lanes operating at the toll station, the congestion will spread from the toll station to freeway basic link through the off-ramp. The exit capacity of toll station is determined by the number of operating MTC and ETC lanes and the existing research \( (18) \) is used in this study (FIGURE 3 (e)). Taking 491pce/h/ln as an example, it means when there are three exit lanes operating at the toll station, and one is ETC lane, then the average exit capacity of these three exit lanes is 491pce/h/ln and the total exit capacity of the toll station is 491*3=1473pce/h.
3.3 Model Validity Checking

In order to ensure the reasonable model run, validity checking is needed to see whether all the simulated vehicles can finish their trips and the model results are convergence.

First, the cumulative departure/arrival curves and the number of vehicles in the network are calculated to check whether all the vehicles can exit the freeway network. The time-dependent travel demand during 7:00am-9:00am on July 23rd (204,076 vehicles) is used as test example. Assume the demand is loaded equally in each 15min interval and only one iteration is processed. As shown in FIGURE 4 (a), the number of vehicles in network increased from 7:00am and reached the maximum at 9:00am. There were no vehicles entering the network after 9:00am so the departure vehicle curve remained constant; while there were still vehicles in the network so the arrival vehicle curve still increased. All the vehicles left the network at 13:25pm and at that time the number of vehicles in the network was zero and the cumulative departure vehicles equaled to the cumulative arrival vehicles. These indicate that all the simulated vehicles can finish their trips and there is no vehicle blocked in the network.

Then, RG is calculated to check whether the model is convergence. The actual time distribution of travel demand during 7:00am-9:00am on July 23rd is used and the maximum iteration number is set as 50 and all the vehicles follow DUE criterion. When RG is smaller than 5%, the model results are considered to be convergence. Load 100%, 150% and 200% travel demand respectively, and the RG of each iteration is shown in FIGURE 4 (b-d). It is found that all the RG are less than 5% and finally keep stable. The results indicate that the model is convergence.

<table>
<thead>
<tr>
<th>Link Type</th>
<th>Speed Limit (km/h)</th>
<th>Jam Density (pce/km/ln)</th>
<th>Lane Capacity (pce/h/ln)</th>
<th>Shock Wave Speed (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeway Basic Link</td>
<td>120</td>
<td>180</td>
<td>2400</td>
<td>15.0</td>
</tr>
<tr>
<td>Normal Toll Station On-ramp</td>
<td>100</td>
<td>180</td>
<td>2300</td>
<td>14.6</td>
</tr>
<tr>
<td>Normal Toll Station Off-ramp</td>
<td>60</td>
<td>180</td>
<td>1200</td>
<td>7.5</td>
</tr>
<tr>
<td>Mainline Toll Station On-ramp</td>
<td>60</td>
<td>180</td>
<td>min(1200, exit capacity of toll station/off-ramp lane number)</td>
<td>Based on lane capacity</td>
</tr>
<tr>
<td>Mainline Toll Station Off-ramp</td>
<td>120</td>
<td>180</td>
<td>2400</td>
<td>15.0</td>
</tr>
<tr>
<td>Interchange Ramp</td>
<td>60</td>
<td>180</td>
<td>min(2400, exit capacity of toll station/off-ramp lane number)</td>
<td>Based on lane capacity</td>
</tr>
<tr>
<td>ETC Lanes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ETC Lanes</td>
<td>3</td>
<td>491</td>
<td>434</td>
<td>379</td>
</tr>
<tr>
<td>ETC Lanes</td>
<td>2</td>
<td>727</td>
<td>588</td>
<td>501</td>
</tr>
<tr>
<td>ETC Lanes</td>
<td>3</td>
<td>914</td>
<td>732</td>
<td>628</td>
</tr>
<tr>
<td>ETC Lanes</td>
<td>4</td>
<td>——</td>
<td>813</td>
<td>745</td>
</tr>
<tr>
<td>ETC Lanes</td>
<td>5</td>
<td>——</td>
<td>853</td>
<td>751</td>
</tr>
</tbody>
</table>

**FIGURE 3 Structure and Attribution of Freeway Network**
The validation aims to evaluate the accuracy of model results when comparing with the field data. The time-dependent travel demand of the whole day of July 23rd 2012 was loaded with 15min interval (96 time intervals totally). The freeway toll records and traffic count detectors were used to validate the model results on network level, OD level and link level. All the simulated vehicles followed DUE criterion and the iteration stopped when RG was smaller than 5%.

4.1 Network-wide Validation

Two indicators, Vehicle Miles Traveled (VMT) and Vehicle Hours Traveled (VHT), were utilized to validate the model results on network level. The distance of shortest path between each OD was used to calculate the actual VMT combining with real TDOD. The actual travel time of each vehicle was obtained by the entry/exit time of freeway toll record. The model results of VMT and VHT was computed automatically by DTALite. The accuracy of VMT and VHT in the 96 time intervals was evaluated by Mean Absolute Percentage Error (MAPE). The total and time varying VMT and VHT is shown in FIGURE 5.

<table>
<thead>
<tr>
<th>Total Entry Vehicles (veh/day)</th>
<th>Total VMT (veh*km)</th>
<th>Total VHT (veh*hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Result</td>
<td>942,999</td>
<td>64,146,802</td>
</tr>
<tr>
<td>Actual Result</td>
<td>948,604</td>
<td>62,086,471</td>
</tr>
<tr>
<td>Diff. (100%)</td>
<td>-0.6%</td>
<td>3.3%</td>
</tr>
<tr>
<td>MAPE of 96 time intervals (100%)</td>
<td>1.1%</td>
<td>9.3%</td>
</tr>
</tbody>
</table>
The difference of total VMT and VHT are both lower than 5% in FIGURE 5(a) and the variation tendency is consistent with the reality in FIGURE 5 (b, c). Meanwhile, the MAPE of VMT and VHT in the 96 time intervals are both lower than 10%. These indicate the dynamic traffic model can represent the time-dependent traffic condition precisely on network level. It is interesting to find that the total model VMT is higher while the VHT is lower than the actual ones in FIGURE 5 (a). And this phenomenon is significant during the AM and PM peak in FIGURE 5 (b, c). This is mainly caused by the dynamic route choice. When the freeway network is congestion during the peak hour, the dynamic route choice model will find the shortest path based on experienced travel time for the travelers. This leads to the travelers choose a longer distance path but cost less travel time. However, in reality not all the travelers have perfect knowledge of the time-dependent traffic condition and they may choose the shortest distance path but not the least travel time. This difference causes the higher VMT but lower VHT of model results.

4.2 OD-based Validation

Small passenger car (P1) was chosen as the analyzing object of OD-based validation. Four OD pairs that the daily OD volume of P1 was larger than 1000veh/day were randomly selected to evaluate the accuracy of OD travel time. The constraint on OD volume was to ensure there were enough toll records to calculate the time-dependent OD travel time. The selected OD locations and model results are shown in FIGURE 6. The results indicate that the model has a good performance on OD level. The difference of average daily travel time is around 10% and the MAPE of time-dependent travel time are all under 15%. FIGURE 6 (b-e) shows the time-dependent travel time of field data and model results. During the time period of 0:00am-6:00am and 20:00pm-00:00am, the variation of actual travel time is significant. The traffic volume is low in these time periods, so the variation is not caused by the traffic condition but by the individual factors such as driving behavior, vision condition and fatigue degree that the dynamic traffic model cannot simulate right now.
4.3 Link-based Validation

The time-dependent link traffic volume of 25 traffic count detectors on Huning freeway are obtained for link-based validation. Aggregated the detector data in 15min interval and there were
96*25=2400 data points available for validation. The detector locations and the comparison between field data and model result is shown in FIGURE 7. The model results are consistent with the field data and the MAPE of these 2400 data points is 15.8%. The time-dependent traffic volume of four links is shown in FIGURE 7 (c-f). It can be found that the time-dependent link volume of model results are consistent with the field data. These results indicate that the dynamic traffic model can represent the time-dependent traffic condition accurately on link level.

FIGURE 7 Link Volume Comparison between Field Data and Model Results
5 WORK ZONE SCENARIO TEST

5.1 Scenario Design

After model results validation, the dynamic traffic model of Jiangsu freeway network can be applied to work zone scenario test. The scenario is to analyze the time-dependent traffic condition when the work zone exists and evaluate the traffic operation management strategies. The work zone located on the link between Suzhou North and Dongqiao (FIGURE 8 (a)). The link capacity dropped to 50% during the construction time period from 8:00am to 16:00pm, July 23rd 2012. The model analyzing time period is the whole day and the analyzing time interval is 15min. Two scenarios were tested: (1) there was no traffic information about the work zone; (2) variable message signs (VMS) were utilized to provide traffic information about the work zone.

In scenario one, all the travelers knew nothing about the work zone until they reached the construction link. In this case, the traffic condition of the work zone network relates with three elements: the time-dependent travel demand, the dynamic route choice under DUE condition when there was no work zone in the network, and the network with work zone. In scenario two, the variable message signs can provide the current traffic condition of the whole network to the travelers when they go through the VMS locations. The travelers change to follow RRC criterion when receiving the traffic information and they may change their route based on the instantaneous travel time.

The model building process of the two scenarios can be seen in FIGURE 8 (b). The normal network reached DUE at the 15th iteration. The work zone existed at the 16th iteration and the equilibrium is broken so the RG increased immediately. If there was no traffic information, the situation of the 16th iteration is scenario one, otherwise is scenario two. If continue the iteration, the network reached DUE again at the 35th iteration. It means the work zone lasted for 20 days and the travelers learned the time-dependent traffic condition of the freeway network with work zone. Then, the travelers adjusted their route choice and reached DUE again. It is the ideal traffic condition when the work zone exists. However, it is quite difficult to achieve this traffic condition on the 1st day because it is impossible to let all the travelers have a comprehensive knowledge about the traffic condition of the network with work zone in such a short time.
### 5.2 Scenario One: Work Zone without Traffic Information

The time-dependent traffic condition of the network with work zone is represented in FIGURE 9. The width of the block means the traffic volume and the color of the block means the travel speed. It is obviously that the traffic congestion spread from the construction link to east and south (i.e. 14:00pm) through Suzhou North interchange and the influenced area was expanding when the work zone exists (i.e. comparing 16:00pm with 14:00pm). When the construction of the work zone was finished and the link capacity recovered, the vehicles that were stuck in the upstream link drove into the work zone with higher traffic volume (i.e. 17:00pm) and the congestion started to release. The model results can identify the most congested links around the work zone area when there is no traffic information. This can help freeway administrators making more effective traffic operation management strategies.
5.3 Scenario Two: Work Zone with Traffic Information

As seen in FIGURE 8 (a), several VMS were located in the network to provide the current traffic information. A response rate specified by the user in DTALite was used to represent the proportion of the travelers who were affected by the information when they pass through the VMS links. If a traveler was affected by the VMS, a new shortest path from the end of the VMS link to the traveler’s destination was updated based on instantaneous travel time. Noteworthy, the new path may be the same with the previous one that based on the DUE assignment results. VMS information and model results are shown in FIGURE 10.

(a) VMS Information of Each Strategy

<table>
<thead>
<tr>
<th>Strategy No.</th>
<th>VMS Location</th>
<th>Operation Time Period</th>
<th>Response Rate (100%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VMS1</td>
<td>8:00AM-22:00PM</td>
<td>60%</td>
</tr>
<tr>
<td>2</td>
<td>VMS2</td>
<td>8:00AM-22:00PM</td>
<td>60%</td>
</tr>
<tr>
<td>3</td>
<td>VMS3</td>
<td>8:00AM-22:00PM</td>
<td>60%</td>
</tr>
<tr>
<td>4</td>
<td>VMS1</td>
<td>8:00AM-16:00PM</td>
<td>60%</td>
</tr>
<tr>
<td>5</td>
<td>VMS2</td>
<td>8:00AM-16:00PM</td>
<td>60%</td>
</tr>
<tr>
<td>6</td>
<td>VMS3</td>
<td>8:00AM-16:00PM</td>
<td>60%</td>
</tr>
<tr>
<td>7</td>
<td>VMS1, VMS2, VMS3</td>
<td>8:00AM-22:00PM</td>
<td>60%</td>
</tr>
<tr>
<td>8</td>
<td>VMS1, VMS2, VMS3</td>
<td>8:00AM-16:00PM</td>
<td>60%</td>
</tr>
</tbody>
</table>

(b) Effectiveness of Each VMS Strategy

<table>
<thead>
<tr>
<th>Strategy No.</th>
<th>VMS Effectiveness</th>
<th>Compare with Scenario One</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Network VHT (10,000 veh*hour/day)</td>
<td>Network VMT (10,000 veh*km/day)</td>
</tr>
<tr>
<td>1</td>
<td>81.2</td>
<td>8335</td>
</tr>
<tr>
<td>2</td>
<td>81.4</td>
<td>8343</td>
</tr>
<tr>
<td>3</td>
<td>83.1</td>
<td>8337</td>
</tr>
<tr>
<td>4</td>
<td>80.9</td>
<td>8348</td>
</tr>
<tr>
<td>5</td>
<td>81.1</td>
<td>8353</td>
</tr>
<tr>
<td>6</td>
<td>83.0</td>
<td>8342</td>
</tr>
<tr>
<td>7</td>
<td>81.0</td>
<td>8335</td>
</tr>
<tr>
<td>8</td>
<td>80.8</td>
<td>8347</td>
</tr>
<tr>
<td>Scenario One</td>
<td>87.6</td>
<td>8331</td>
</tr>
</tbody>
</table>
In FIGURE 10 (b), the VMS1 has the best performance on releasing congestion when only one VMS is used. The reason is that there were 43.6% work zone volume that passing VMS1 while there were only 10.8% that passing VMS3. VMS1 can affect more travelers than VMS3. However, there were 65.8% work zone volume passing through VMS2 while the traffic condition performance of VMS2 is not as good as VMS1. In FIGURE 9, the congestion spread over VMS2 location and it means the vehicles had to drive through a section of congestion before they got the traffic information from VMS2. This is why VMS2 had a higher VHT than VMS1 although VMS2 had a larger work zone volume percentage. It can also be noticed that the longer operation time period of VMS had a better performance because the congestion time period was longer than the construction time period. The travelers still needed the traffic information to guide them in avoiding the congested links after the construction finished. Meanwhile, the traffic condition had the best performance when all the three VMS worked together for a long time period in this scenario. The change of time-dependent volume of link1 and link2 (FIGURE 8 (a)) is shown in FIGURE 10 (c, d). It also can indicate that some vehicles changed their previous route choice and make a detour to avoid the work zone based on VMS information.

6 CONCLUSION

This paper demonstrates the application of dynamic traffic model on the traffic operation management of freeway network. Unlike the models using estimated TDOD, real TDOD provided by freeway toll record after data quality control is utilized in this study and this ensures the demand of the model is consistent with the reality. It is a pioneering study to establish the dynamic traffic model of freeway network based on toll record in China and the results indicate that the model has great performance on the description of time-dependent traffic condition and the evaluation of traffic operation management strategies.

After demand and supply preparation, the model validity checking shows that all the generated vehicles can leave the network and the model result is convergence. Freeway toll records and traffic count data have been applied to validate the model results on three levels: network, OD and link. The absolute difference of daily total VMT and VHT of the whole network is less than 5% and the MAPE of 96 time interval is below 10%. The absolute difference of average daily travel time of the four selected OD pairs are around 10% and the MAPE of the 96 time interval is less than 15%. The MAPE of 2400 data points about time-dependent link volume is 15.8%. The validation results indicate that the model has high accuracy on representing time-dependent traffic condition. And then, work zone scenario test shows the model can identify the time-varying influenced area and evaluate different VMS settings. The model can assist the administrators when making operation management strategies.
Although this study makes a great improvement on the analyzing ability of time-dependent traffic condition of the large scale freeway network, there are still several challenges. This study shows the work flow of off-line application that the TDOD of the entire analyzing time period is known directly from historical dataset. However, the on-line application of dynamic traffic model is also needed when analyzing the real-time traffic condition, and this requires the real time TDOD. Freeway toll records can provide detailed historical TDOD information. How to use the historical information to realize the short term prediction of TDOD is one of the further research direction. Moreover, the impact of different vehicle types on traffic condition is represented by static PCE in this study, while the impacts of heavy vehicles change with traffic condition. How to describe the dynamic interaction among small passenger cars and heavy vehicles in dynamic traffic model is another further research point.

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REFERENCES