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Calibrating and Modeling Expressway with Different Ramp Distances on Beijing 3rd Ring Road

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Abstract

As a typical bottleneck connecting freeway and common road, ramp is an important traffic congestion area. Various traffic phenomena near ramps can be described by the Cell Transmission Model (CTM). However, real traffic data shows that traffic flow characteristics are far different for the ramp system with different ramp distances. We analyze traffic characteristics of ramp system with both an on-ramp and an off-ramp in Beijing 3rd ring road firstly. Then, it is found that ramp distance between the on-ramp and the off-ramp has a great impact on the capacity, due to the conflict of traffic flow between on-ramp and off-ramp. Finally the traffic conflict is considered in the merge cell and Capacity Drop CTM (CD-CTM) is proposed to embody the conflict. The simulation results suggest that CD-CTM fits the empirical data from Beijing 3rd ring road.

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Keywords: urban traffic flow; cell transmission model; ramp system; urban expressway

1. Introduction

Traffic congestion is an inevitable problem in most large cities all over the world. In order to suppress traffic jams and increase the capacity of the road networks, the nature way is to build new infrastructures. Particularly, expressways are developed rapidly in some large cities of China, such as Beijing, Shanghai, and so on. Although expressways provide advantage service for traveling, ramps connecting expressways and local roads become new
bottlenecks, which usually induce congestions. To understand the nature of congestions, theoretical traffic flow models have been developed and calibrated with empirical data. CTM is a famous traffic flow model presented by Daganzo (1994, 1995). In CTM, road is divided into homogenous cells. This model clearly describes the interaction between neighboring cells. It relies on a sending function depending only on the state of upstream cells, and on a receiving function depending on the state of downstream cells. CTM provides an intuitively appealing and easy approach to deterministically describe how the number of vehicles in consecutive cells of a freeway evolves over consecutive time intervals. So far, CTM has been extensively investigated and extended, e.g. LCTM (Lagged Cell Transmission Model) by Daganzo (1999), EL-CTM (Enhanced Lagged Cell Transmission Model) by Szeto (2009), and MCTM (Modified Cell Transmission Model) by Muñoz et al. (2004). Furthermore, many applications for ramp systems have been done by using CTM, e.g. Lebacque (1996); Jin and Zhang (2003); Gomes et al. (2003, 2006, 2008); Saidi et al. (2010).

Since real traffic data is the basis for traffic flow modeling, both theoretical and practical methods are combined in this work to promote the reliability of the conclusions. To solve traffic problem near ramps in urban expressway, traffic flow characteristics must be studied firstly. In this work, the famous CTM model is used to depict the dynamics of traffic flow, due to its simplicity, high efficiency, and flexibility for extension. Above all, the most important reason is that CTM can reproduce most phenomena in real traffic, such as shock waves and so on. However, the expressway ramp system, together with the various driving behaviors in China, induces much more traffic flow states, which cannot well be depicted by the original CTM. As a consequence, based on empirical traffic data obtained in Beijing 3rd ring road, the CTM is validated and calibrated for various systems with an on-ramp and an off-ramp. It is found that ramp distance has a great impact on capacity. Especially in small distance cases, the capacity drops off. For these system, the Capacity Drop CTM (CD-CTM) is proposed to reflect traffic conflict in the merge cell. The model is applied to Beijing 3rd road. The simulation results show that, both CD-CTM can depict traffic flow characteristics for the expressway ramp systems with different ramp distance.

2. Traffic Characteristics of Ramp Systems in Beijing 3rd Ring Road

In this paper, data collecting points are from Beijing 3rd ring road. These points are Zhao Gong Kou Bridge west, Hang Tian Bridge north, and Nong Zhan Bridge south, and labeled by Points 1 to 3 orderly. The inside circle is the inner road, and the outside one is the outer ring. Points 1 are located in inner road, while points 2, 3 are in the outer road. Traffic data is obtained through Remote Traffic Microwave Sensor (RTMS) during 5:00-23:00 on May 13, 2010.

All systems on these three observation points are ramp systems with an on-ramp and an off-ramp. We define the ramp distance as the distance between two adjacent ramps. The ramp distances on the points 3, 2, and 1 are distinct, and are respectively 95m, 220m, and 360m. The effect of ramp distance on traffic flow characteristics can be investigated in accordance with the real data detecting in these points.

In Fig. 1(a), the flow-density diagrams are plotted according to real traffic data. These scatter points can be classified into three regions, free-flow region with low density, semi-stable region with medium density, and congestion region with high density. In the free-flow region, the flux increases linearly with the density. In the semi-stable region, the flux reaches the maximal value. In the congestion region, the flux decreases with density. By comparing with the flux-density diagram for different ramp distances, an interesting phenomenon can be found. In the system with ramp distance of 360m, scatter data points are mainly located in free-flow region, and more data points are located in large density region as ramp distance decreases. Furthermore, the maximum flow increases with ramp distance, but the corresponding critical densities are nearly the same.
Fig. 1. (a) Flux; (b) average flux versus density for various ramp distances

Fig. 2(a) shows that, as the ramp distance increases, more data distributes in free-flow region which coincides with the result in Fig. 1(a). In Fig. 2(b), the ramp system with a larger ramp distance has a trend with larger velocities. Fig. 2(c) displays standard deviation of the velocity to describe the velocity fluctuation. One can see that, the system with the ramp distance of 360m has a large velocity fluctuation. For the systems with ramp distances of 95m and 220m, the velocity fluctuations have no obvious difference.

Fig. 2. (a) Velocity; (b) average velocity; (c) standard deviation of velocity versus density for various ramp distances.

3. Data Calibration for Beijing 3rd Ring Road

3.1. Parameter calibration for CTM

In CTM, four parameters need to be calibrated. They are free flow velocity, maximum flow, congestion back-wave velocity, and jam density, respectively.

- Free Flow Velocity \( v_f \)
  Free flow velocity is the maximum velocity on road, where the interaction between vehicles can be neglected. So the average velocity at low density is set as free flow velocity. The average velocity, flow-density diagram and fundamental diagram of scatter point on Nong Zhan Bridge south are shown in Fig. 3. \( v_f \) is also the slope of flow-density curve in low density area in Fig. 3(b) and Fig. 3(c).

- Maximum Flow \( q_{\text{max}} \)
  The maximal average flow is the capacity of traffic flow on roads. \( q_{\text{max}} \) is the maximum value in Fig. 3(b) and Fig. 3(c).

- Congestion Back-wave Velocity \( w \) and Jam Density \( \rho_{\text{jam}} \)
  The jam density and congestion back-wave velocity are estimated by using data during morning peak 8:00-9:00 by performing a least-squares fit for the flow-density relationship. During this time period, nearly all data is located on the congestion branch. \( w \) is set as absolute value of the slope of flow-density curve in high density area. The point where the high density region regression line crosses zero flow is considered as the jam density \( \rho_{\text{jam}} \). The fitted fundamental diagram of Nong Zhan Bridge south is labeled by solid lines in Fig. 3(c).
Fig. 3. (a) Velocity-density; (b) average flow-density; (c) fundamental diagram of scatter data on Nong Zhan Bridge south

- Calibration Results

The parameter calibration method mentioned above is applied to the 3rd ring road in Beijing. Aiming at different ramp distances, calibration results are shown in Table 1.

Table 1. Parameters of CTM for different ramp distance cases.

<table>
<thead>
<tr>
<th>ramp distance (meter)</th>
<th>$V_f$ (kilometer/hour)</th>
<th>$q_{max}$ (vehicle/hour)</th>
<th>$W$ (kilometer/hour)</th>
<th>$\rho_{jam}$ (vehicle/kilometer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>95</td>
<td>47.73</td>
<td>1432.38</td>
<td>11.12</td>
<td>192.46</td>
</tr>
<tr>
<td>220</td>
<td>50.13</td>
<td>1523.89</td>
<td>10.38</td>
<td>209.39</td>
</tr>
<tr>
<td>360</td>
<td>51.19</td>
<td>1690.18</td>
<td>11.32</td>
<td>207.68</td>
</tr>
</tbody>
</table>

From Table 1, we can see that, the case with the larger ramp distance has the larger maximal flows. These results are in accordance with the traffic flow data analyzing in section 2.

3.2. Cell Transmission Model

- Link Model

In CTM, road sections are divided into a series of homogenous cells. It is assumed that the flow and the density comply with the trapezoidal fundamental diagram, as shown in Fig. 4, where $\rho_{jam}$, $q_{max}$, $V_f$, $W$ respectively denote the jam density, maximum flow, free-flow velocity, and velocity of the backward shock wave. Then, flow-density relationship can be expressed as,

$$q = \min\{\rho V_f, q_{max}, W(\rho_{jam} - \rho)\} \quad (1)$$

![Diagram of CTM](image)

Fig. 4. The trapezoidal fundamental diagram of CTM

The basic concept of CTM is to divide the road into homogenous cells (as shown in Fig. 5) and time into intervals, such that the cell length is equal to the distance traveled by free flowing traffic in one time interval. Then the flows are related to the current conditions at time $t$ as indicated in Eq. (2). The vehicle number at time $t+1$ equals its vehicle number at time $t$, plus the inflow vehicles and minus the outflow vehicles, as in Eq. (3).
\[ f_i(t) = \min \{ n_{i-1}(t), Q_i(t), w[N_i(t) - n_i(t)] / v_i \} \]  
\[ n_i(t + 1) = n_i(t) + f_i(t) - f_{i+1}(t) \]  

where, \( f_i(t) \) is the inflow of cell \( i \) for time interval \( t \), \( n_i(t) \) is number of vehicles in cell \( i \) for time interval \( t \), \( Q_i(t) \) is the maximal allowable inflow of cell \( i \) for time interval \( t \), \( N_i(t) \) is the maximal number of vehicles allowable in cell \( i \) for time interval \( t \). 

In Eq. (2), the minimum value of the first two terms in the right side is the number of vehicles that cell \( i-1 \) can send for time interval \( t \), and is denoted as \( S_{i-1}(t) \). Similarly, the minimum value of the last two terms is equivalent to vehicles that cell \( i \) can receive for time interval \( t \), and is represented as \( R_i(t) \). Eq. (2) can thus be rewritten as:

\[ f_i(t) = \min \{ S_{i-1}(t), R_i(t) \} \]  

- **Merge Model**

Fig. 6 shows vehicles of upstream cell \( i \) on mainline and vehicles of on-ramp cell \( i' \) merging into downstream cell \( i+1 \). Assuming that, the total inflow of cell \( i+1 \) at time \( t \) is \( f_{i+1}(t) \), and the inflow of cell \( i+1 \) from cell \( i \) and cell \( i' \) are \( f_i(t), f_i(t) \) respectively. \( p_i(t) \), \( p_i(t) \) are the inflow percentage of \( f_i(t) \) and \( f_i(t) \) to \( f_{i+1}(t) \). The outflow of cell \( i \) and cell \( i' \) are calculated as follows,

\[ f_i(t) = f_{i+1}(t)p_i(t), f_i(t) = f_{i+1}(t)p_i(t) \]  

- **Diverge Model**

For a diverge situation in Fig. 6, vehicles in mainline upstream cell \( i-1 \) enter into mainline downstream cell \( i \) and off-ramp cell \( i' \). Assume that total outflow of cell \( i-1 \) for time interval \( t \) is \( f_{i-1}(t) \), and inflow of cell \( i \) and cell \( i' \) from cell \( i-1 \) are \( f_i(t) \), \( f_i(t) \) respectively. \( h_i(t) \) and \( h_i(t) \) are percentage of \( f_i(t) \) and \( f_i(t) \) to \( f_{i-1}(t) \). \( f_i(t) \) and \( f_i(t) \) are calculated as follows,

\[ f_i(t) = f_{i-1}(t)h_i(t), f_i(t) = f_{i-1}(t)h_i(t) \]
4. Modified Cell Transmission Model for Systems with Different Ramp Distances

According to the discussions in sections 2 and 3, the ramp distance has great influences on traffic flow. In this section, a modified CTM model will be proposed to consider the effect of the ramp distance.

4.1. Modified CTM for various ramp distances

- Simulation Results with CTM
  The distances for observation points 3, 2, 1 are 95 m, 220 m and 360 m respectively. Using calibrated parameters in section 3, the three systems are simulated with CTM, as shown in Fig. 7. The simulation data shows a larger deviation than the empirical data in medium density area. CTM can’t depict real traffic phenomenon well in this density area, and thus needs to be modified.

- CD-CTM (Capacity Drop CTM)
  Conflicts may frequently appear at the merge cell, due to the interaction between the flows from upstream mainline and on-ramp. As a result, the capacity of merge cell decreases. Assuming that the capacity of merge cell $Q_i'(t)$ decreases linearly with the inflow of on-ramp, $Q_i'(t)$ can be expressed as follows:

\[ Q_i'(t) = \frac{(1 - y)Q_i(t) - r_i(t) + Q_i(t)}{Q_{\text{ramp}}(t)} \]

\[ f_i(t) = \min\{n_i(t), Q_i'(t), w[N_i(t) - n_i(t)]/v \} \]

where $Q_{\text{ramp}}(t)$ is the maximal allowable outflow on on-ramp at time $t$, $y$ is the percentage of minimum capacity of merge cell to its original value, and $r_i(t)$ is the real inflow from on-ramp into mainline. In Eq. (8), if $r_i(t) = 0$, then $Q_i'(t) = Q_i(t)$; if $r_i(t) = Q_{\text{ramp}}(t)$, then $Q_i'(t) = yQ_i(t)$. In other words, if no on-ramp vehicle enters mainline, $Q_{\text{ramp}}(t)$ doesn’t change, otherwise it decreases. This model is called as CD-CTM (Capacity Drop CTM).

- Simulation Results with CD-CTM
  The systems with the ramp distance of 95m, 220m, 360m are closest to empirical data when $y$ is set respectively as 88.5%, 92.5% and 96.5%. Thus, $y$ is set as 88.5%, 92.5% and 96.5% respectively for the three systems in the following. The simulations are carried out by both CTM and CD-CTM for the three road systems, as shown in Fig. 8.
and Table 2. From Fig. 8 and Table 2, it is found that in medium density area, the standard deviations in CD-CTM decrease greatly. Thus, CD-CTM can reflect real traffic phenomenon better than CTM.

Fig. 8. The standard deviation of flow under both CTM and CD-CTM

Table 2. The average standard deviation of flow at different density regions.

<table>
<thead>
<tr>
<th>density region</th>
<th>low region</th>
<th>medium region</th>
<th>high region</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTM(veh/h) when ramp distance is 95 m</td>
<td>52.08</td>
<td>126.09</td>
<td>47.48</td>
</tr>
<tr>
<td>CD-CTM(veh/h) when ramp distance is 95 m</td>
<td>51.33</td>
<td>65.52</td>
<td>50.42</td>
</tr>
<tr>
<td>CTM(veh/h) when ramp distance is 220 m</td>
<td>62.13</td>
<td>135.17</td>
<td>68.74</td>
</tr>
<tr>
<td>CD-CTM(veh/h) when ramp distance is 220 m</td>
<td>61.63</td>
<td>59.69</td>
<td>62.72</td>
</tr>
<tr>
<td>CTM(veh/h) when ramp distance is 360 m</td>
<td>63.96</td>
<td>114.34</td>
<td>51.45</td>
</tr>
<tr>
<td>CD-CTM(veh/h) when ramp distance is 360 m</td>
<td>63.97</td>
<td>38.63</td>
<td>38.74</td>
</tr>
</tbody>
</table>

5. Conclusions

Different ramp cases in Beijing 3rd ring road display various traffic phenomena. Thus, traffic flow data is firstly analyzed in the system with different ramps. It is found that small ramp distance between ramps causes a capacity drop. CTM parameters are calibrated, but the standard deviation in the medium density region is far different from the real data. Then, based on data analysis, CTM is modified to fit different ramp cases. For the system with different ramp distance, vehicles’ conflict at the merge cell is considered and CD-CTM (Capacity Drop CTM) is proposed. It suggests that, CD-CTM can decrease the deviation of simulation flow in medium density area. As a conclusion, CD-CTM can better depict traffic phenomena near ramps.

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References


