Study on the Impact of Urban Traffic Capacity due to the Lane Occupation

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Abstract. We aim to investigate the problem of the impact of lane occupation on urban road traffic capacity and vehicle queuing length. We successfully solve the degrees of impact of different lane occupation on the actual road capacity, the relationship among the vehicle queuing length and the cross-section actual capacity and traffic flow on upstream by the theories of speed-flow model and improved traditional cumulative reach-leaving model. Through the analysis of examples, we conclude that the model presented in this paper is reasonable and can be used in practice to solve the relevant problems.

The lane occupation means the cross section of the traffic road becomes narrow because of the traffic accident, temporary roadside parking, work and other factors, which always lead to traffic jams. Because of the characteristics of traffic flow density, strong continuity on the city road, if a lane is occupied, it may reduce the road all the lanes of traffic capacity. Even though the time is very short, it may also be caused by traffic jams. If it is treated inappropriately, traffic jams would become terrible.

In China, lane occupation is very common. To estimate correctly the influence degree of the city road traffic capacity due to the lane occupation, it will provide a theoretical basis for the traffic administrative department, on the correct guide vehicle, reasonable examination and approval work, set the curb parking and setting non harbor shaped bus station etc.

Keywords: Traffic capacity; speed-flow model; cumulative reach-leaving model

1. Introduction

In this paper, we have established a mathematical model according to the video of the CUMCM-2013 Problem A. First, we define the calculation formula of the actual capacity, and collect traffic-flow data in the video and the Video, so as to obtain the change process of the accident to evacuate during the actual capacity of the cross section. Through the test of variance, we show that there is different actual capacity influence when a traffic accident happens on the different lane in the same section of
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traffic accidents. Then we build the model about road capacity loss rate by using the relationship between road traffic capacity and road space, and get the degree of influence on the actual capacity owing to the different lane occupation. Second, we improve the traditional reach-leaving model. Through the improved traditional reach-leaving model, we analyze the influence of road traffic accident vehicle queue length and cross section of the actual capacity of accident, accident duration, the relationship between the upstream sections of vehicle flow, vehicle queue length estimation model is established. Finally, we apply this model to calculate queuing length and queuing disappear duration in the two kinds of traffic accident cases.

2. Assumptions

1. The ratio of vehicle flow in each lane doesn’t change because of the traffic accident.
2. Once the lane occupied, we believe no vehicle can go through the lane.
3. We believe that only the four wheel vehicle and above vehicle, battery car on the road.
4. We believe that the vehicle queue length relate to the actual traffic capacity of the cross section, and accident duration, and sections upstream traffic flow, no other factors are involved.

3. Model building and solving

3.1. Analysis the actual traffic capacity of different lane

3.1.1. Calculate the actual traffic capacity

We can calculate the road capacity under the overload traffic conditions by use of the common highway speed-flow model. We hope get a function relation of speed and flow under any traffic load conditions. We obtain the average speed and traffic load through the following model given by Wang [1].

\[
\begin{align*}
U &= \frac{\alpha_1 U_s}{1 + \rho^\alpha} \\
\tau &= \alpha_1 + \alpha_2 \cdot \rho^3 \\
\rho &= \frac{V}{N}
\end{align*}
\]

(1)

where \(U\) is the average speed, \(U_s\) is that the design speed of the highway, \(\rho\) is the traffic load, \(V\) is vehicle flow, \(N\) is the traffic capacity, \(\alpha_1\) is 1.133, \(\alpha_2\) is 1.88 and \(\alpha_3\) is 4.90.

Further, we need to learn the maximum traffic capacity on every road which can pass in a unit of time under the ideal traffic conditions. According to the model given by Li [2], we can get the maximum traffic capacity.

\[
N_{\text{max}} = \frac{3600}{t_0} = \frac{3600}{l_0 / (U / 3.6)} = \frac{1000V}{l_0}
\]

(2)

Because the vehicle front minimum interval \(l_0\) is relate to the safety distance \(l_s\), between it and the front vehicle and it usually take as 3 to 5 meters, the average length of
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the vehicle \( l_c \), the driving distance \( l_f \) within the driver’s reaction time of vehicle and braking distance \( l_b \). From the above, we get the formula \( l_0 = l_c + l_f + l_b + l_i \).

According to Gong’s research [3], we learn the driver’s reaction time \( t_i \) is generally one second or one second and a half. Let \( \mu \) is the coefficient of friction between the wheel and road surface. Under the ideal conditions, we can get the basic traffic capacity as follow:

\[
N_{\text{max}} = \frac{1000U}{3.6 t_i + \frac{U^2}{254\mu}} + l_c
\]

(3)

However, the traffic capacity in the actual situation is influenced by the lane width, the traffic conditions, the number of lanes and other factors. In order to get the actual situation of the traffic capacity, we improve the model, by additional consideration lane width correction coefficient of traffic conditions, the correction coefficient of correction coefficient, the number of lanes correction coefficient. The model is given by

\[
N_p = N_{\text{max}} \prod_{j=1}^{n} B_j
\]

(4)

Finally, we put the service traffic volume multiplied by a given level of service and the traffic capacity with the ratio, and then can get the actual traffic capacity as follow:

\[
N_s = \frac{N_p \times \text{service traffic volume}}{\text{traffic capacity}}
\]

(5)

We collected traffic flow data from the video \( \text{Video1} \), and convert the traffic flow volume into a standard vehicle equivalent number based on the vehicle conversion factor in table 1.

<table>
<thead>
<tr>
<th>Tape of vehicle</th>
<th>minibus</th>
<th>Large bus</th>
<th>Large trucks</th>
<th>Hinge for vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>conversion factor</td>
<td>1.0</td>
<td>2.0</td>
<td>2.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>

**Table 1:** Vehicle conversion factor

By formula (1) - (4), we can get the average speed, the basic traffic capacity and the actual traffic capacity. We draw a graph to show the actual capacity changes over time by using matlab software, as in Figure 1 (a).

![Figure 1: The actual traffic capacity curve](image)
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According to figure 1(a), we learn the changes of the actual traffic capacity after the accident occurred. By recording the traffic flow within a minute before the accident occurred, we can obtain the traffic capacity is 1686 pcu/h. Compared with the actual traffic capacity, the traffic capacity dropped by 30.72% after the accident. During the whole accident to evacuate, we learned that the cross-sectional actual traffic capacity changes little, about 1168 pcu/h.

3.1.2. Effect of occupying different lane on the actual capacity

Through the analysis of the video I, video II data and figure 1, during the whole accident to evacuate, we can know that there is a different effect on the actual capacity of the same cross section due to the lane different occupied. Through the test of variance (see Table 2), it further illustrates the different lane occupied is an important factor affecting the average traffic capacity.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std Deviation</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>VAR00001</td>
<td>17</td>
<td>1157.00</td>
<td>1180.00</td>
<td>1168.0000</td>
<td>6.3429</td>
<td>40.250</td>
</tr>
<tr>
<td>VAR00002</td>
<td>26</td>
<td>1160.00</td>
<td>1185.00</td>
<td>1172.2414</td>
<td>5.90191</td>
<td>34.833</td>
</tr>
</tbody>
</table>

Table 2: The statistical results of traffic flow form video I and video II

Based on the relationship between traffic capacity and the share of road space, Xu [4] put forward a calculated method and model of lane-changing about it’s effected to additional road space, and calibrated the parameters, the correction factor is calculated. Therefore, we define the road capacity loss rate to show the actual traffic capacity influence degree because of the different lane’s occupying.

In a certain period of time, the vehicles in the unregulated state, the actual traffic capacity because of the lane-changing behavior of influence is relate to the number of lane-changing vehicles. It can be given by

\[ Q_v = (Q - Q_v) \cdot q_t \cdot (V_f \cdot t / l_g) \]

where \( Q_v \) is the road capacity loss.

We consider the effect of shunt accounted for traffic flow ratio \( \varphi_k \), and deduces the total occupy extra space due to the lane changing behavior within in time \( t \).

\[ l_A = (Q - Q_v) \cdot q_t \cdot (V_f \cdot t / l_g) \cdot |\Delta V| \cdot t_c \cdot \varphi_k \]

where \( q_t \) is the probability of the lane-changing behavior occurrence, \( l_g \) is the vehicle traveling distance in free flow speed \( V_f \) in a unit of time, \( \Delta V \) is the difference between the speed after the lane-changing behavior occurrence and the free flow speed \( V_f \).

We need to know the road space of every car occupancy to get the additional space occupation caused by traffic volume loss. We can get it through the formula given by

\[ l_D = \frac{t \cdot V_f}{Q} \]
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Under ideal traffic capacity of road conditions, the traffic volume loss per unit time is the ratio given by

\[
Q_s = \frac{I_s}{I_p} = \frac{(Q - Q_s) \cdot q_i \cdot (t \cdot V_f / l_s) \cdot |\Delta V| \cdot t_e \cdot \varphi_k \cdot Q}{t \cdot V_f} \tag{9}
\]

where

\[
Q = \frac{t \cdot V_f}{l_p} = K_j \cdot V_f / 4 \tag{10}
\]

and \(K_j\) is the jam density.

The road capacity loss rate is defined as the ratio of total loss of traffic volume \(Q_s\) and traffic volume \(Q\). Therefore the formula for calculating the traffic capacity of the road loss rate is

\[
\alpha_c = \frac{Q_s}{Q} = \frac{K_j \cdot V_f \cdot q_i \cdot |\Delta V| \cdot t_e}{4l_s + q_i \cdot |\Delta V| \cdot t_e \cdot \varphi_k \cdot (K_j \cdot V_f)} \tag{11}
\]

Let \(V_f = 60 \text{ km/h}\), \(K_j = 111.1 \text{ pcu} / (\text{km} \cdot \text{ln})\). We use the formula (11) and can get the effect of the traffic capacity because of different lane occupation. The results of the calculation are shown in the following table.

<table>
<thead>
<tr>
<th>Conditions of lane occupation</th>
<th>The loss of traffic flow ratio</th>
<th>The road capacity loss rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2, 3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1, 2</td>
<td>0.65</td>
<td>0.6199</td>
</tr>
<tr>
<td>1, 3</td>
<td>0.56</td>
<td>0.5871</td>
</tr>
<tr>
<td>2, 3</td>
<td>0.79</td>
<td>0.6788</td>
</tr>
<tr>
<td>1</td>
<td>0.21</td>
<td>0.487</td>
</tr>
<tr>
<td>2</td>
<td>0.44</td>
<td>0.5485</td>
</tr>
<tr>
<td>3</td>
<td>0.35</td>
<td>0.5227</td>
</tr>
</tbody>
</table>

**Table 3:** The different effects on the actual capacity of different lane occupied

According to table 3, we can see that the influence degree on the actual capacity due to the different road lane occupied is different. If the first lane is occupied, the impact of the actual capacity is the minimal. Though the same number of lanes is occupied, because traffic flow ratio of every lane is different, and the traffic capacity loss rate is also different. When all the 3 Lanes are occupied, the actual capacity is reduced to 0, that is, the road to traffic. Because the large the road capacity loss rate is, the bigger the degree of influence holds the behavior of vehicle actual capacity is. It shows that the traffic flow and the traffic capacity of the road loss rate is negative correlation.

### 3.2. Vehicle queue length estimation model

Because traffic accidents happen on the upstream road, it leads to a reduction of the section of the actual traffic capacity, and results in traffic congestion, and causes vehicle queuing situation. In order to estimate the vehicle queue length, we select the
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traditional cumulative reach-leaving model. The model can be used to calculate the flow, and the actual flow of the traffic network is relatively easy to obtain, and the model is convenient to be improved according to the characteristics of urban road [5].

There are some defects in the traditional cumulative reach-leaving models, such as the actual traffic capacity of the original model is a constant, and the arrival traffic flow of the car is a monotonically decreasing function. In fact, the actual traffic capacity is not a fixed value and the traffic flow is a monotonically decreasing function, it may be a fluctuating curve with the time.

In order to avoid the above problem, we improve the original model by considering the dynamic changes of the actual traffic capacity and a function of the arrival traffic flow which is obtained according to the signal periodic fitting. Then we use the improved cumulative reach-leaving model to estimate the length of the vehicle queue, and obtain the relation among vehicle queue length, the actual traffic capacity of the cross section, accident duration and the upstream traffic flow.

3.2.1. The relationship among the length of vehicle queue and the actual capacity and upstream traffic flow

Due to the two different cycle of the intersection traffic signal and random arrival, we get the arrival flow diagram according to the data of the vehicle in video. The arrival flow diagram as follow:

![Figure 2: The arrival flow diagram](image)

Using the arrival flow diagram, we can get the formula to calculate the vehicle number of the cumulative arrival. The formula is given by

\[
Q_j(t) = \int Q(t) dt \quad (12)
\]

Similar, we can get the vehicles number of the cumulative leaving by the follow formula.

\[
N_j(t) = \int N_j(t) dt \quad (13)
\]

Therefore, the vehicle numbers of the accumulative arrival and of the leaving are monotonically increasing with the time.

3.2.2. The relationship between the actual traffic capacity and the accident duration

The actual traffic capacity is constantly changing in the traffic accident duration. With the actual traffic capacity to gradually return to normal levels, the actual cumulative traffic capacity will be increased linearly with the increase of time. The length of queue vehicles will shorten to zero with the increase of time.
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Based on the above analysis, we establish the model by considering the relationship among the number of accident vehicle queue, the actual capacity, the upstream traffic flow and the accident duration. The model is

\[ B(t) = Q_j(t) - N_j(t) = \int N_j(t)\,dt - \int Q(t)\,dt = \int (N_j(t) - Q(t))\,dt \]  \tag{14}

Then we can get the length of the vehicles queue by the follow formula.

\[ L(t) = \frac{B(t) \cdot l_p}{\text{number of lanes}} = \frac{l_p \cdot \int (Q(t) - N_j(t))\,dt}{3} \]  \tag{15}

With the continuous change of arrival traffic flow, the queue length may be lengthen or shorten. When \( Q(t) = N_j(t) \), the number of vehicles queuing reaches to the local maxima of this moment. During the period of the traffic accident, the number of extreme point means how many times queuing occurs, only difference of the queue length. The maximum queue length is the maximum value of the extreme point. Therefore, we can get the maximum vehicle queue length from the below formula.

\[ L_{m} = \max_{t_j} \left[ \max (L(t)) \right] \]  \tag{16}

where \( L(t_j) \) is the extreme value of the time \( t_j \).

3.2.3. The calculation

Variables in the model involved is continuous, such as traffic flow, the actual traffic capacity and so on. But we get the value of the variable from the video, which are discrete values. Therefore, we fit the discrete values to obtain a variation of the variables over time. Here we discuss two cases:

**Case 1:** We get the standard vehicle equivalent number from video I, and we obtain the cumulative standard vehicle equivalent number. Then we fit a cubic regression model.

\[ Q_j(t) = 3.926 + 19.629t - 0.371t^2 + 0.025t^3 \]  \tag{17}

Similar, we can get the linear regression equation to calculate the cumulative actual traffic capacity value.

\[ N_j(t) = \begin{cases} 0.978 + 19.238t, & 0 \leq t \leq t_c, \\ 339.182 + 28.1(t - t_c), & t > t_c, \end{cases} \quad (t_c = 17.58 \text{ min}) \]  \tag{18}

From the formula, we get the model to calculate the queue length before and after the accident evacuation. The formula is given by
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\[
L(t) = \frac{l_p \times B(t)}{3} = \begin{cases} 
\frac{l_p}{3} (0.025t^3 - 0.371t^2 + 0.382t + 2.948), & 0 \leq t \leq t_s \\
\frac{l_p}{3} (0.025t^3 - 0.371t^2 - 8.471t - 335.222), & t > t_s 
\end{cases} \tag{19}
\]

**Case 2:** It is 140 meters far from upstream of the intersection to the road traffic accidents, and the accident does not evacuate, and reach the traffic flow at the detection section changes, and the traffic capacity of downstream doesn’t change.

<table>
<thead>
<tr>
<th>Original (N_j)</th>
<th>17</th>
<th>24</th>
<th>22</th>
<th>12</th>
<th>18</th>
<th>14</th>
<th>21</th>
<th>20</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative number</td>
<td>17</td>
<td>41</td>
<td>63</td>
<td>75</td>
<td>93</td>
<td>107</td>
<td>128</td>
<td>148</td>
<td>163</td>
</tr>
<tr>
<td>Original (N_j)</td>
<td>21</td>
<td>19</td>
<td>16</td>
<td>25</td>
<td>20</td>
<td>18</td>
<td>17</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Cumulative number</td>
<td>17</td>
<td>203</td>
<td>219</td>
<td>244</td>
<td>264</td>
<td>282</td>
<td>299</td>
<td>315</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4:** Video accumulated leave and turn the cumulative number of vehicles

By using the data of Table 4, we get the regression model.

\[
N_j(t) = 18.566t + 0.257 \tag{20}
\]

Because the upstream traffic volume traffic is 1500 pcu / h. So we have

\[
Q_j(t) = \frac{1500t}{60} = 25t \tag{21}
\]

From the formula, we get the length of the queue which is given by

\[
L(t) = \frac{l_p}{3} [Q_j(t) - N_j(t)] = \frac{l_p}{3} (6.434t - 0.257) \tag{22}
\]

If \(L(t) = 140\), the length of the vehicle queue will reach to the upstream intersection after 220 seconds, i.e. once accident occurs, the vehicle queue length will reach the upstream intersection after 220 seconds.

**4. Conclusion**

In this paper, focusing on CUMCM-2013 Problem A, we have established the actual capacity model due to different lane occupied and the vehicle queue length estimation model. Then we correct the actual traffic capacity gradually and get an improved reach-leaving model which can be more reasonable to solve practical problems.

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