Empirical Study on Relationship among the Lane-Changing, Speed and Traffic Flow

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Abstract

Lane-changing behavior in weaving segment of urban expressway in transportation engineering is a significant factor contributing to the loss of capacity. This paper attempts to analyze the statistical relationships among lane-changing, speed and density of traffic flow in different lanes of weaving segment of urban expressway under a given traffic condition and general levels of service. Based on the analysis result, a series of models is recommended. The effectiveness between the recommended models and the existing model is compared. Although the optimization effect not very clear, but the lane-changing factors have some relationship with the traffic characteristics in weaving segment of urban expressway.

Keywords: number of lane-changing; transportation engineering; weaving segment; speed; density

1. Introduction

Urban expressways are the artery of urban traffic which generally have many entrances to control access and own most of characteristics of freeway. The levels of service often remain at level three to level four in peak hours of everyday. Lane-changing behaviors can easily lead to chaos of traffic flow, reduce capacity significantly and even accidents. Studying the relationship and the degree of influence among the Lane-changing behaviors, speed and density in different lanes of weaving segment of urban expressway under different levels of service is an important subject of traffic flow and capacity.

2. Reference review

The study of the influence of Lane-changing behavior to traffic flow started from Lighthill and Whitham (1955), Richards (1956) who put forward the famous “LWR” model\textsuperscript{[1-2]}. Munjal (1971) et al believed that lane-changing vehicles could change speed instantaneously and could not hinder the following vehicles\textsuperscript{[3-9]}. The research of Laval and Daganzo (2003)\textsuperscript{[10]} proved that lane-changing vehicles had a significant influence on following vehicles\textsuperscript{[11-13]}, and further set up the relationship models of speed, density, flow and lane-changing

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rate[14]. The content of lane changing did not mentioned in HCM2000[15]. Previous studies have all demonstrated that lane-changing behaviors do have influence on traffic flow. However, it lacks of empirical analysis, especially the research on different lanes in weaving segment of urban expressway under general levels of service remains blank. This paper attempts to establish statistical relationships among lane-changing, speed and density through measured data within 5 minutes interval. Based on the result, a series of models and range of parameters values are recommended. Then we compare the fitting effect of the recommended models with those of the existing models.

3. Concepts and research methods

3.1. Concepts and premise research conditions

Urban expressway central separated, have one-way multi-lanes and supporting facilities for traffic safety and management, the spacing and forms of entrances are controlled completely[16]. Weaving segment is the district where vehicles weaves. In normal circumstances, the length of weaving segment is 30m to 750m[17,18]. The distance between entrances of the third round road in Chengdu city satisfies the length of weaving segment, and the designed speed of lanes are 100km/h, 80km/h and 60km/h. In this paper we divide the lanes into fast lane (lane 1), intermediate lane (lane 2 and lane 3) and slow lane (lane 4) basing on the designed speed. Lane-changing behavior is a comprehensive behavior which includes driver’s response to the speed and neutral of vehicles around and changing to another lane[19].

The traffic conditions we study on includes: the weaving segment of urban expressway; the main vehicles styles involve cars, middle buses (trucks), a few large buses (trucks) and motorcycle; we carry out data collection in working days (9:00—20:00, including the peak hours).

The road conditions we study are: eight lanes of two-way, standard wide of lanes.

3.2. Research method and process

Via the video shoot method proposed in HCM2000[15], we obtain a large amount of data with 5 minutes interval offline. The study process involves drawing scatter diagrams, choosing fitting models, regression analysis, testing models, determining the interval of parameters and concluding.

4. Data collection and processing

4.1. Data collection and the calculation of minimum sample size

The 4 selected survey segments are all entrances of the third round road of Chengdu city which connect with flyovers in different line-types (4 in all). Surrounding segments are mainly commercial and residential houses, and exist pedestrian overcrossings which can provide convenient place to shooting videos. The situations are showed in Table.1 and Fig.1. The data within 5 minutes interval which are used for regression analysis should satisfy the minimum sample size, which can be estimated by Eqs. (1).

\[
N = \frac{Z^2 \sigma^2}{E^2 K^2}
\]

Where N is the minimum sample size of observational data; \(\sigma\) is the standard deviation of observational speed samples; \(K\) is a constant corresponding to the confidence level which fulfill the expectation; \(E\) is the permissible error of speed which depends on the precision of average speed, generally taking the value of 1.5 to 2km/h.

We bring \(\sigma=7\text{km/h (Zhang et al (2007) [18])}\), \(K=1.96\text{ (95%)}\) and \(E=2\text{km/h}\) into Eqs. (1), then \(N=48\).
4.2. Data obtained method

We obtained $v_i$, $n_i$ and $l_i$ of each lane by Hi-pro MTC-10 which is an instrument for collecting data of traffic flow. Using Li’s (2002)\cite{20} photography method, we obtain the density $K$ with 5 seconds’ interval of each picture, and bring the values into Eqs. (2).

\[
K = \frac{\sum_{i=0}^{n} K_i}{n} \times \frac{1}{L}
\]  

(2)

Where $n$ is the number of pictures in total time and $T$ is the total time(s); $K_i$ is the number of vehicles exists in the observation interval on picture $i$; $L$ is the length of observation distance.

Table 1. The statistics of shooting conditions

<table>
<thead>
<tr>
<th>Survey segments</th>
<th>Distance(m)</th>
<th>Shooting time</th>
<th>Total minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>300</td>
<td>2011.1.12 and 1.13</td>
<td>525</td>
</tr>
<tr>
<td>B</td>
<td>300</td>
<td>2011.1.12 and 1.13</td>
<td>610</td>
</tr>
<tr>
<td>C</td>
<td>200</td>
<td>2010.5.27, 5.28, 7.21, 2011.1.5, 1.11 and 1.12</td>
<td>455</td>
</tr>
<tr>
<td>D</td>
<td>200</td>
<td>2011.1.13 and 1.18</td>
<td>710</td>
</tr>
</tbody>
</table>

Tips: the distance of each survey segment is determined by the signature distance which is convenient to calculate.

Fig. 1. Survey segments

4.3. Analysis of scatter diagrams
The grouping of measured data by different levels of service in different lanes is showed in Table 2. We select the data from the lanes within the levels of service between level 3 and level 4 and N48, then the scatter diagrams of speed-density, speed-number of vehicles of enter lane, speed-number of vehicles of exit lane, density-number of vehicles of enter lane and density-number of vehicles of exit lane.

<table>
<thead>
<tr>
<th>Levels of service</th>
<th>density v/c data</th>
<th>Lane 1</th>
<th>Lane 2 and lane3</th>
<th>lane4</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS one</td>
<td>≤12</td>
<td>0~0.51</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>LOS two</td>
<td>≤19</td>
<td>0.51~0.71</td>
<td>77</td>
<td>0~0.67</td>
</tr>
<tr>
<td>LOS three</td>
<td>≤26</td>
<td>0.71~0.85</td>
<td>61</td>
<td>0.67~0.83</td>
</tr>
<tr>
<td>LOS four on half</td>
<td>≤42</td>
<td>0.85~1.0</td>
<td>102</td>
<td>0.83~1.0</td>
</tr>
<tr>
<td>LOS four on the second half</td>
<td>&gt;42</td>
<td>&gt;1.0</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2 (a) shows that speed appear a obvious stratification under different levels of service in different lanes. Fig. 2 (b) - Fig. 2 (e) shows that the gap in the times of lane-changing under different density and speed is slight. So it is necessary to take regression analysis.

5. Regression model optimization

5.1. Model analysis and sample expansion

We examine the distribution of $V_s$, $n_1$, $n_2$ and $K$ as normal distribution.

The data distributions of $V_s$, $n_1$, $n_2$ and $K$ have no significant difference with normal distribution. We analyse the data by SPSS and the results are shown in Table 3.

<table>
<thead>
<tr>
<th>Level of service</th>
<th>$V_s$</th>
<th>$n_1$</th>
<th>$n_2$</th>
<th>$K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>lane1 LOS three</td>
<td>0.026</td>
<td>0.110</td>
<td>0.670</td>
<td>0.450</td>
</tr>
</tbody>
</table>
Taking \( \beta \), since the values of gradual significance (double tails) of \( \beta, \beta_1, \beta_2 \) and \( \beta_3 \) are greater than \( \beta \), we consider \( \beta \) accepted.

We presume that the relationship among \( K, V_s, n_1 \) and \( n_2 \) can be described in Eqs.(3).

\[
K = f(V_s, n_1, n_2)
\]  

We analyse the linear correlation between \( V_s \), and \( n_1 \), \( n_2 \) and by SPSS. The results are shown in Table.4.

Table 4. The gradual significant (double tails) in distribution examination of \( V_s, n_1, n_2 \) and

<table>
<thead>
<tr>
<th>Speed</th>
<th>Rate of entering lane</th>
<th>Rate of exiting lane</th>
<th>Level of service</th>
</tr>
</thead>
<tbody>
<tr>
<td>lane1 density</td>
<td>-0.944**</td>
<td>0.410</td>
<td>0.338</td>
</tr>
<tr>
<td></td>
<td>-0.950**</td>
<td>0.603**</td>
<td>0.438</td>
</tr>
<tr>
<td>lane2 density</td>
<td>-0.948**</td>
<td>0.485</td>
<td>0.503</td>
</tr>
<tr>
<td></td>
<td>-0.955**</td>
<td>0.556</td>
<td>0.614**</td>
</tr>
<tr>
<td>lane3 density</td>
<td>-0.961**</td>
<td>0.677**</td>
<td>0.632**</td>
</tr>
</tbody>
</table>

Tips: The ‘’**’’ represents the significant linear correlation between two factors under the confidence level.

It can be seen that the linear correlation between speed and density is strong, while the relationship among density, number of vehicles of enter lane and exit lane need further study. Meanwhile, any group (48 articles) arbitrarily selected from the existing data are not enough to obtain the statistics relationship among density, speed and times of lane-changing. But the data of previous 5 minutes will not influence those of the following 5 minutes. Combining any 48 articles as a group arbitrarily, we can obtain the groups of 1775,2350,1775,1775 and 1775. The mixed fitting curves from different groups can satisfy the statistics regression analysis, especially the estimation of parameters interval. We transform the times of lane-changing of each group via linear, Index, logarithms, power function and polynomial etc. then fit via Eqs.(4).

\[
K = aV_s + bn_1 + cn_2 + d
\]  

Where \( a, b, c \) and \( d \) are all parameters.

The calculation shows that the relationship between \( V_s \), and \( K \) is linear (showed by the existing research and also can be judged from scatter plots), while \( n_1 \) and \( n_2 \) obtain better fitting results when transformed as linear, Index (two ways), logarithms and power function and polynomial which are shown in Tab.5.

Table 5. The mean value of fitting degree and variance under different transforms of \( n_1 \) and \( n_2 \)

<table>
<thead>
<tr>
<th></th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
<th>Model 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean value</td>
<td>mean value</td>
<td>mean value</td>
<td>mean value</td>
<td>mean value</td>
</tr>
<tr>
<td>LOS three</td>
<td>0.88151</td>
<td>0.875749</td>
<td>0.883863</td>
<td>0.884071</td>
<td>0.877972</td>
</tr>
<tr>
<td>variance</td>
<td>0.00148</td>
<td>0.001872</td>
<td>0.001384</td>
<td>0.001372</td>
<td>0.001768</td>
</tr>
<tr>
<td>the upper half of LOS four</td>
<td>0.91331</td>
<td>0.9146</td>
<td>0.912424</td>
<td>0.912327</td>
<td>0.914477</td>
</tr>
<tr>
<td>variance</td>
<td>0.00045</td>
<td>0.000444</td>
<td>0.000441</td>
<td>0.000438</td>
<td>0.000458</td>
</tr>
<tr>
<td>LOS three</td>
<td>0.89236</td>
<td>0.895447</td>
<td>0.89301</td>
<td>0.893128</td>
<td>0.896142</td>
</tr>
</tbody>
</table>
The mean values and variances of five models are different which is showed in Tab.5. We can learn that model 4 is the best model for lane 1 while model 5 for lane 2 and lane 3 from the comprehensive comparison of mean values and variances.

Lane 1:

\[ K = aV_s + bLN(n_1) + cLN(n_2) + d \]  \hspace{1cm} (5)

Lane 2 and lane 3:

\[ K = aV_s + b^n_1 + c^n_2 + d \]  \hspace{1cm} (6)

Where a, b, c, and d are all parameters.

### 5.2. The determination of value range of model parameters

The regression analysis on data via Eqs. (5) and (6) by EXCEL can obtain the fitting degree, related parameters of formulas, value and interval of parameters \( t \) under level three and the upper half of level four.

We choose and test the significance of each parameter by T test:

- \( H_0 \) : The values of a, b and c are 0
- \( H_1 \) : The values of a, b and c are not all 0

If we receive the rejection region when \( \alpha \). The result shows the value of \( \alpha \) receives the rejection region and the regression effect is significant. We get the value intervals of parameters in Table.6.

Table 6. The value internal of each parameter under different levels of service

<table>
<thead>
<tr>
<th>Lane 1</th>
<th>Lane 2</th>
<th>Lane 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS three</td>
<td>the upper half of LOS four</td>
<td>LOS three</td>
</tr>
<tr>
<td>d</td>
<td>[25.817, 42.973]</td>
<td>[25.817, 42.973]</td>
</tr>
<tr>
<td>a</td>
<td>[-0.262, -0.172]</td>
<td>[-0.262, -0.172]</td>
</tr>
<tr>
<td>b</td>
<td>[-1.127, 2.0494]</td>
<td>[-1.127, 2.0494]</td>
</tr>
<tr>
<td>c</td>
<td>[-2.914, 1.6975]</td>
<td>[-2.914, 1.6975]</td>
</tr>
</tbody>
</table>

### 5.3. Models comparison

According to the linear relationship between \( K \) and \( V_s \) which was proposed by Green Shields and still adopted in model “LWR”, we carry on linear regression via Eqs. (7) and compare the mean value of fitting degree via Eqs. (5) and (6) in Table.7.

\[ K = aV_s + b \]  \hspace{1cm} (7)

Where \( a \) and \( b \) are parameters.

Table 7. The comparison of fitting degree between recommend formulas and exist formula

<table>
<thead>
<tr>
<th>Level of service</th>
<th>Lane 1</th>
<th>Lane 2</th>
<th>Lane 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS three</td>
<td>the upper half of LOS four</td>
<td>LOS three</td>
<td>the upper half of LOS four</td>
</tr>
<tr>
<td>Eqs.(5) and (6)</td>
<td>0.884071</td>
<td>0.912327</td>
<td>0.896142</td>
</tr>
<tr>
<td>Eqs. (7)</td>
<td>0.873376</td>
<td>0.909923</td>
<td>0.887797</td>
</tr>
</tbody>
</table>
The mean values of fitting degree of recommend formulas are better than those of existing formulas as shown in Table 7. The phenomenon illustrates that density not only has something to do with speed but also the vehicle number of enter lane and exit lane. But the difference of fitting degree between recommend and exist formulas is slight.

6. Conclusion

From the analysis above, we know that there exist nonlinear relationship among density of traffic flow and the mean speed of interval, number of vehicles of enter lane and exit lane in different lanes under LOS three and the upper half of LOS four as shown in Eqs. (5) and (6). The average speeds of urban expressway in non-block situation distribute above 20km/h. The difference of fitting degree between recommend and exist formulas is small, but the value of the recommend formulas is still higher than the existing one. So we think that density is not only related to speed but also to the vehicle number of enter lane and exit lane.

In this paper, we only put forward the relationship among density, speed, vehicle number of lane-changing in weaving segment of urban expressway in different lanes and under LOS three and the upper half of LOS four, which are only under the conditions of workday, cloudy without rain and commercial and residential houses around. Then the recommend formulas and the interval of related parameters are given. Many further research, such as the relationship among times of lane-changing, speed and density under the situations of other LOS, different land use, different time, different weather and other urban roads of such as urban main roads, secondary roads, slip roads etc. will be studied in future.

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