Study on the evaluation of merging traffic streams on the urban expressway in Osaka
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Abstract

One of the prime objectives of the study is to evaluate the differences between the night-time and the day-time merging traffic stream characteristics by analyzing the merging traffic survey data covering night-time and day-time as well as congested and non-congested traffic conditions. A previously developed merging traffic computation model considering multi-merging phenomena was applied to evaluate the traffic in terms of merging probability.

1 Background and objectives of study

Traffic congestion on urban expressways in Japan increases annually because of heavy traffic demand. Urban expressways have very complicated networks with many radial and ring roads and consequently there are many weaving, merging and diverging sections which cause various forms of bottlenecks. In particular, merging points add traffic to the main traffic volume which increases downstream traffic volume.
significantly, creating bottleneck sections with traffic demand exceeding capacity. In addition the highway authorities in Osaka are paying attention to nighttime expressway traffic conditions following the opening of the new Kansai airport, which is open for 24 hours a day. In situations such as those described above, increasing attention is being paid to merging traffic phenomena on expressways with respect to through traffic streams with their headlights on at night or through secluded spaces in tunnels or semi-underground structures. It is considered very useful to study and evaluate nighttime expressway merging traffic patterns in order to develop future traffic operations on expressway networks in large metropolitan areas. One of the prime objectives of this study is to evaluate the differences between nighttime and daytime merging traffic streams by analyzing merging traffic survey data covering both nighttime and daytime congested and non-congested traffic conditions. In this study a series of traffic surveys were conducted at the Minatomachi merging section on the Central Ring of the Hanshin Expressway in Osaka.

2 Outline of the merging probability model

Assumptions for model building are as follows;

i) Gaps in the through traffic as well as those in the on-ramp traffic are assumed to follow the Erlang distribution.

ii) The maximum number of vehicles assumed on calculating the multiple merging probability is three.

iii) The multiple merging probability is calculated for the on-ramp vehicles merging into the main traffic stream in which diverging traffic through the downstream off-ramp is included. The number of lanes of the main roadway is two.

The probability density functions, hereafter " the pdf ", of the gaps in the main and ramp traffic are as shown below:

Main traffic; \[ f_i(x_i) = \frac{\lambda_i}{(k_i-1)!} \cdot (\lambda_i \cdot x_i)^{k_i-1} \cdot e^{-\lambda_i x_i} \]  
(1)

On-ramp traffic; \[ g(y) = \frac{\lambda_0}{(k_0-1)!} \cdot (\lambda_0 \cdot y)^{k_0-1} \cdot e^{-\lambda_0 y} \]  
(2)
Where $k_i$, $\lambda_i$, and $k_0$, $\lambda_0$ are the Erlang Distribution parameters for the main and ramp traffic flow respectively, and $i$ is the lane number with $i = 1$ corresponding to the shoulder lane and $i = 2$ corresponding to the median lane. With the application of the Erlang distribution, the relationships between parameters are as shown below:

$$\frac{k_i}{\lambda_i} = \frac{t}{Q_i}, \quad \frac{k_0}{\lambda_0} = \frac{t}{q}$$

(3)

Where $Q_i$ : The number of vehicles in lane $i$ in the main traffic counted during the time period $t$.
$q$ : The number of ramp vehicles counted during the time period $t$.
$t$ : The time period in seconds during which these traffic volumes are measured.

The pdf of the headway between an arbitrary merging vehicle and the vehicle running behind on the main traffic lane at the moment when the merging vehicle reaches the ramp nose [$f_{si}(x_i)$] is obtained as the starting density of $f_i(x)$ as shown below:

$$f_{si}(x_i) = \frac{1}{r_i} \sum_{n=1}^{k_i-1} \frac{(\lambda_i \cdot x_i)^n}{n!} \cdot e^{-\lambda_i \cdot x_i}$$

(4)

$$g_i(y) = \frac{1}{g} \sum_{n=1}^{k_0-1} \frac{(\lambda_0 \cdot y)^n}{n!} \cdot e^{-\lambda_0 y}$$

(5)

Where $r_i$ and $g$ are the average gap lengths of lane $i$ of the through traffic and the ramp traffic respectively.

In a multiple merging situation, the headway between the $(j+1)$ position merging vehicles and the first merging vehicle that takes the lead in a multiple merging situation is the sum of the $j$ random variables which have the Erlang distribution with parameters $k_0$ and $\lambda_0$. Therefore the pdf of the headway to the $(j+1)$ position merging vehicle [$g_i(y)$] is expressed by applying the rule of addition to the random variables as follows:

$$g_i(y) = \frac{\lambda_0}{(j k_0 - 1)!} \cdot (\lambda_0 y)^{j k_0 - 1} \cdot e^{-\lambda_0 y}$$

(6)

Using the basic equations from (1) to (6), computation logic for single and more than double situations merging can be described as follows:

Consider a single merging into the road lag in the shoulder lane. Conditions for the single merge are 1) the ramp vehicle is the first merging
vehicle, and 2) the following vehicle merges into the next upstream gap as shown in Figs.1 and 2. Definitions of the variables in Fig. 1 are as follows:

- $x_{s1}$ and $x_{s1}^{'},$ The front and the rear traffic lags expressed respectively to the shoulder lane vehicle in the main traffic.
- $Y_{1}^{'}$ and $Y_{1},$ The headways to the preceding ramp vehicle and to the following ramp vehicle, respectively.
- $\tau_{30},$ The critical acceptable rear lag in the shoulder lane of the main traffic.

When the merge of an on-ramp vehicle to the first lag in the shoulder lane is not possible, then the on-ramp vehicle attempts to merge into the following gap. The merging probability to the following gap is calculated by considering the probability of a simultaneous occurrence of four conditions like those shown in Fig. 1 and 2.

The merging probability for multiple on-ramp vehicles can also be calculated by comparing the difference between a lag or gap on the shoulder lane and the sum of gaps of ramp vehicles with the critical acceptable lag.
3 Outline of the traffic survey

A series of traffic surveys were conducted at the merging area of the Minatomachi section of the Central Ring of the Hanshin Expressway in Osaka. The traffic surveys were conducted on Wednesday the 20th, Thursday the 21st and Saturday the 22nd of August in 1997 to collect traffic data covering both congested and noncongested periods during daylight and nighttime conditions. Traffic conditions at the merging area of both on-ramp terminals were recorded by video cameras setup on the rooftops of the neighboring buildings of the survey area. Five minute durations of lane traffic volume were measured from the recorded video tape and the time periods for data reduction were selected as shown in table-1.

<table>
<thead>
<tr>
<th>Table-1 Data Reduction Periods</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Non Congested Periods</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Congested Periods</td>
</tr>
</tbody>
</table>

In order to confirm the effects of traffic flow on measuring gap distribution and critical acceptable gaps necessary to compute merging probability using the merging-model, running speed was measured on both the upstream and downstream sections as well as on the merging zones for each lane. The length of the merging zone is 100 meters followed by a 30 meter merging section to the median lane of the Sakai Line. Fig.3 shows fifteen minute durations of lane traffic volume during the data reduction periods respectively. It is suggested that the shoulder lane traffic volume becomes much less than other traffic lane volumes on the Central Rings. Fig.4 shows the results of running speed measurements for the daylight conditions.

Next, Fig.5 shows the results of merging gaps and traffic lag measurements during the daytime and nighttime as well as congested and noncongested traffic data reduction periods. The merging gaps and lags were measured manually by stopwatch at the merging point and then confirmed by the video tape recording based on measurement aid lines drawn cross-sectionally on the video playback screen. The aid lines were drawn to represent a pitch of about three meters, because the location of the merging point of each vehicle from the on-ramp differs from vehicle to vehicle. The critical value in Fig.5 is the 85 percentile.
Fig. 3 Fifteen Minutes Lane Traffic Volume During Data Reduction Period

Fig. 4 Average Running Speed of the Study Section
value of the measurements. The reason why the critical value during congested periods is greater than that during free flow traffic conditions is considered to be a result of the gaps which accept the merging vehicles in the congested flow tend to become longer especially during the nighttime.

In order to confirm the lane use of each vehicle through the study section during each data reduction period, all of the vehicles running through the study section were further analyzed on the video playback screen and the lane usage of each vehicle at the check point was recorded during each data reduction period. Table-2 shows the ratio of the number of vehicles staying on the same lane at the downstream section compared to the number of vehicles at the upstream section. Table-2 indicates the higher difficulty in making lane changes during

Table-2  Lane Keeping Ratio Through Study Section

<table>
<thead>
<tr>
<th></th>
<th>Daytime</th>
<th></th>
<th>Nighttime</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Non-Congested</td>
<td>Congested</td>
<td>Non-Congested</td>
</tr>
<tr>
<td>1st Lane of the Sakai Line</td>
<td>86.1</td>
<td>84.9</td>
<td>79.5</td>
</tr>
<tr>
<td>1st Lane of the Central Ring</td>
<td>56.9</td>
<td>63.4</td>
<td>57.5</td>
</tr>
<tr>
<td>2nd Lane of the Central Ring</td>
<td>76.4</td>
<td>83.7</td>
<td>67.1</td>
</tr>
<tr>
<td>3rd Lane of the Central Ring</td>
<td>80.7</td>
<td>90.6</td>
<td>70.9</td>
</tr>
</tbody>
</table>
congested flow conditions during both daytime and nighttime traffic conditions.

4 Evaluation based on merging probability

4.1 Input Data

Input data necessary to use the merging probability model are lane traffic volume including the ramp itself (\( q_i \) and \( q_r \)), parameters of Erlang distribution (\( k_1 \) and \( k_0 \)), critical acceptable gaps and lags (\( T_0 \) and \( T_{so} \)), maximum number of rejected gaps for each merging vehicle (\( n \)) and the lane changing rate for merging vehicles. The following are descriptions of the input data determined from the results of the merging traffic survey:

i) Parameters of Erlang distribution (\( k_1 \) and \( k_0 \)).

The parameters of the Erlang distribution for the traffic flow on the shoulder lane of the through traffic and for the ramp (\( k_1 \) and \( k_0 \)) gap measurements data were divided into gap classes with 0.5 second increments so as to include more than five measurements in each gap class. The \( x^2 \) value was computed using the equation of the test of conformity varying the value of \( k_1 \) and \( k_0 \) from one to ten. Finally the value of \( k_1 \) and \( k_0 \) were determined by taking the values of \( k_1 \) and \( k_0 \) that give the minimum values of the value \( x^2 \). Results for the Tsukamoto survey section as a computation example are shown in table-3. Table 3 shows the list of the input data of \( k_1 \) and \( k_0 \) for the computation of merging probability.

ii) Critical acceptable gaps and lags.

Critical values of the acceptable gaps and lags are shown in Fig.5 as the results of gaps and lags measurement data reduction are used as input data for the merging probability computation process.

iii) Maximum number of rejected gaps.

The maximum number of rejected gaps is the maximum number of gaps that each merging vehicle can reject until the driver finds an acceptable gap to merge into the through traffic. Since there are some merging vehicles that pass over two or three gaps until they can find a gap long enough to merge into the shoulder lane, the maximum number of rejected gaps is set to be three.
iv) Lane changing rate for merging vehicles (\( p_e \)).
The lane changing rate for the merging vehicles is defined as follows:
In merging probability models, it is assumed that there are a certain
number of drivers who make a lane change into their median side lane
upon noticing a merging vehicle when they are using the shoulder
lane. The lane changing rate is determined from the results of lane
change measurements in which the number of vehicles making lane
changes on noticing the merging vehicle(s) within a ten meter down-
stream range is confirmed during the data reduction periods. These
results are shown in table-3.

Table-3  Lane Changing Rate for Giving Way to Merging Vehicle

<table>
<thead>
<tr>
<th></th>
<th>Number of Confirmed Vehicle</th>
<th>Number of Lane Changing vehicle</th>
<th>Lane Changing Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daytime</td>
<td>22</td>
<td>8</td>
<td>36.36</td>
</tr>
<tr>
<td>Nighttime</td>
<td>21</td>
<td>8</td>
<td>38.10</td>
</tr>
</tbody>
</table>

4.2 Evaluation of Merging Traffic based on Merging Probability

Table-4  Merging Probability during Data Reduction Period

<table>
<thead>
<tr>
<th>Period</th>
<th>Non-congested</th>
<th>Congested</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daytime</td>
<td>96.25</td>
<td>86.52</td>
</tr>
<tr>
<td>Nighttime</td>
<td>87.38</td>
<td>85.33</td>
</tr>
</tbody>
</table>

Table-4 shows the merging probability computation results for all four
conditions using the merging probability model based on the
input data described in the previous section. Table-4 shows that the
daytime merging probability is higher than the nighttime merging
probability, and that the merging probability under free flow condi-
tions is higher than under congested flow conditions. However, the
probability difference may be brought about partly because of the dif-
fERENCE of lane traffic volume. Therefore, in order to evaluate the
effect of traffic volume on merging probability, the merging proba-
bility was computed by changing the through traffic volume
before the merging nose from 900 veh./hr. to 2100 veh./hr. and the
ramp traffic volume from 100 veh./hr. to 1300 veh./hr. with the same
value of input data for shoulder lane volume distribution rate, critical
acceptable gaps and lags as well as Erlang distribution parameters. The results of the computation are illustrated as probability contour line charts as shown in Fig.6. It is shown that all of the solid contour lines for nighttime conditions show a slightly higher merging probability than the broken lines for daytime conditions under free flow traffic conditions. Conversely, all of the broken contour lines for daylight conditions show a higher merging probability than the solid contour lines for nighttime conditions for all the combinations of the through traffic and ramp traffic volume under congested flow conditions as shown in Fig.6. It can be estimated that daylight expressway merging is easier than merging into expressway traffic with headlight-on conditions in artificially illuminated underground structure under congested flow conditions. In order to compensate for such merging difficulties, particular attention should be paid to appropriate countermeasures such as geometric design improvements.

Fig.6 Probability Contour Diagram
5 Conclusions and subjects for further study

In this study, a series of traffic surveys were conducted at the Minatomachi merging section of the Central Ring of the Hanshin Expressway in Osaka to obtain merging traffic data covering both daytime and nighttime congested and non-congested traffic conditions. The merging traffic flow was evaluated based on the merging probability using the survey results. The results of the study are as follows:

i) Using the merging probability model, the merging probability can be calculated for both congested and noncongested merging traffic by using Erlang distribution parameters that give the minimum $X^2$ value for both congested and non-congested traffic conditions.

ii) By comparing the merging probability for both the daylight and nighttime merging traffic conditions, daytime merging probability is found to be higher than nighttime merging probability for almost all combinations of ramp and through traffic volume situations, under congested flow conditions.

Expected subjects for future study are as follows:

In this study, the merging probability was computed for various values of ramp and through traffic volumes with constant input data which was determined from the survey data. However, most of the input data such as Erlang distribution parameters and critical acceptable gaps and lags can be fitted to various traffic conditions if there is sufficient merging traffic data. Additional traffic surveys should be continued in order to obtain sufficient merging traffic data.

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