A Study of Collision Risk Estimation and Users Evaluation at Merging Section of Urban Expressway in Japan

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Abstract
This study aims to estimate collision risk by using a surrogate safety measure and discusses the quality of service perceived by drivers at merging sections of an urban expressway in Japan. First, to elucidate collision risk occurrences at merging sections, we analyzed the collision risk between a merging vehicle and a main lane vehicle by using the Possibility Index for Collision with Urgent Deceleration (PICUD). Second, we performed discriminant analyses of the PICUD estimation results to reveal the factors influencing collision risk at each merging section for several conflict patterns. The discriminant analyses revealed that the merging position, traffic volume of the main lane, and direction of merging section have a significant effect on the collision risk for merging movements.

Keywords: Collision risk, User evaluation, Merging section, Urban expressway

1 Introduction
Spatial constraints at urban expressways in Japan cause several problems. Because of spatial constraints, the lengths of some merging sections are insufficient and these sections comprise a right-hand-side entrance ramp that is directly connected to the main lane. This causes stress to unfamiliar and elderly drivers and they perceive collision risks while merging onto the expressway. Therefore, these situations must be quantitatively evaluated from the viewpoints of traffic conflict risk and the quality of service perceived by drivers.

Makigami and Matsuo (1988) analyzed the critical gap for a left-hand-side merging section (hereinafter side-ramp) and a right-hand-side merging section (hereinafter center-ramp) on an urban expressway; however, they did not evaluate the quality of service (hereinafter QOS) at the merging sections. In addition, Ohsawa et al. (2010) analyzed the characteristics of vehicle movements in the
acceleration lane at a center-ramp, and Ogino et al. (2003) evaluated the effects of reducing traffic congestion by analyzing the vehicle movements at a center-ramp; however, they also did not discuss the QOS at the merging sections. Using a simulation model, Makigami et al. (1984) evaluated traffic safety at merging sections on an expressway by using traffic conflict data such as braking and lane-changing behaviors. Kita and Hirai (1993) developed a merging behavior model considering merging timing coordination and evaluated the potential risk at merging sections by using the time to collision (TTC) index. In addition, Watanabe and Nakamura (2005) or Chu et al. (2013) developed the gap choice behavior model and acceleration movement model for merging sections. Moreover, Akutsu and Iwasaki (2005) analyzed the QOS at merging sections by using detector data from the point of applicability of the evaluation index at a basic section.

As stated above, many studies have evaluated the gap choice behavior and acceleration behavior of coordinating vehicles at merging sections on urban expressways. However, the potential risk after gap choice behavior at a merging section has not been evaluated using a surrogate safety measure (hereinafter SSM). Moreover, the relationship among traffic situation, road structures of merging sections, and certain conflict patterns has not been analyzed from multiple viewpoints.

Therefore, this study aims to estimate collision risk by using an SSM and discusses the QOS perceived by drivers at merging sections of an urban expressway in Japan. Using image processing technology, we observed vehicle merging movements and traffic conflicts at three ramps with different geometries.

2 Characteristics of Survey Site

We evaluated vehicle movements at three ramps (merging sections) on Nagoya Expressway in Nagoya city, Japan. Figure 1 shows the merging section geometries.

![Merging section geometries](image)

(a) Side-ramp

(b) Center-ramp

Figure 1 Merging section geometries
The structural characteristics of the subject ramps are shown in Table 1, and the Q–V diagrams for each ramp are shown in Figures 2, 3, and 4. It can be seen that we have considered ramps with various structures and a wide range of traffic situations.

The average traffic volumes [veh/5 min] of the main lanes, into which the vehicles directly merge, were 152, 103, and 67 for ramps A, B, and C, respectively. That is, the volume to capacity ratio (v/c) for A, B, and C were about 0.8, 0.6, and 0.4, respectively.

Table 1 Structural characteristics of the three ramps

<table>
<thead>
<tr>
<th>Ramp (Ramp type)</th>
<th>Length of acceleration lane [m] (Length of zebra zone)</th>
<th>Taper length[m]</th>
<th>Total length of merging section[m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (Center-ramp)</td>
<td>200(65)</td>
<td>80</td>
<td>280</td>
</tr>
<tr>
<td>B (Center-ramp)</td>
<td>125(30)</td>
<td>75</td>
<td>200</td>
</tr>
<tr>
<td>C (Side-ramp)</td>
<td>135(40)</td>
<td>25</td>
<td>160</td>
</tr>
</tbody>
</table>

Figure 2 Q–V diagram for the fast lane for ramp A

Figure 3 Q–V diagram for the fast lane for ramp B
3 Aggregate Analysis of Merging Behaviors

3.1 Analysis of Merging Position

We quantified vehicle movement data including vehicle trajectories, velocity, and acceleration from video image data collected at 0.1 s intervals using an image processing system.

We evaluated the merging movements and surrounding situations for 2 h at each ramp and focused on the traffic conflicts between a merging vehicle and the forward and/or rearward vehicles in the lane adjacent to the merging section. For the merging behavior measurement, we defined the starting point as the beginning of the zebra section and the ending point as the termination of the taper section. Moreover, when a vehicle’s side edge crossed the marking of the main lane, merging movement was considered to have started, and when the vehicle’s other side edge crossed the marking of the main lane, merging movement was considered to have ended. We measured the merging position for each vehicle as the ratio of the distance between the starting and merging points to the total length due to the different total length of 3 merging sections. We compared the characteristics of the merging positions for the three ramps with different structures on the basis of this ratio. In this study, we use the relative position as the index of position of merging section due to the limited number of ramps. Therefore, we will do additional research on the other multiple ramps with similar structure and discuss the influence of the absolute position (in meter of length) in the future.
Figure 5 shows the merging starting position for each ramp. It can be observed that for ramp A, the merging starting position is at a smaller percentage of the merging section compared with those for the other two ramps. This is because the traffic volume of ramp A is the greatest among the three, and hence, the drivers tend to consider that if the merging position becomes downstream of the merging section, they will not be able to find an appropriate gap between the main traffic and merge safely.

### 3.2 Conflict Analysis at Merging Section Using Surrogate Safety Measure

We adopted the Possibility Index for Collision with Urgent Deceleration (PICUD) to evaluate the rear-end collisions under the following situation. This index was proposed by Uno et al. (2001), and it is defined as the distance between the leading and following vehicles when the leading vehicle has rapidly decelerated and the following vehicle has started to decelerate with a reaction delay time and stopped with urgent deceleration. PICUD is expressed by Equation 1. A negative index value implies that a crash has occurred.

\[
PICUD = \frac{V_1^2}{2a_1} - \left( V_2 \Delta t + \frac{V_2^2}{2a_2} \right) + s_0
\]

where
\(V_1\): Speed of the leading vehicle just when it starts to decelerate [m/s]
\(V_2\): Speed of the following vehicle just when the leader starts to decelerate [m/s]
\(s_0\): Distance between the leading and following vehicles at the timing of urgent deceleration [m]
\(a_1\): Deceleration rate of the leading vehicle [m/s\(^2\)] (assumed to be “2.95(0.3G)”[ m/s\(^2\)] in this study)
\(a_2\): Deceleration rate of the following vehicle [m/s\(^2\)] (assumed to be “2.95(0.3G)”[ m/s\(^2\)] in this study)
\(\Delta t\): Reaction delay time [s] (assumed to be “1.0”[s] in this study)

We attempted to estimate three types of traffic conflicts occurring at a merging section: (1) the conflict between a merging vehicle and the leading vehicle in the adjacent main lane, (2) the conflict between a merging vehicle and the following vehicle in the adjacent main lane, and (3) the conflict between a merging vehicle and both the leading and following vehicles in the adjacent lane.

To evaluate traffic safety at the merging section, we focused on the minimum PICUD during the merging behavior for each vehicle and measured the traffic conflicts with a negative PICUD for every 10% interval at each ramp. Here, we defined the proportion of risky incidents as the ratio of the number of negative PICUD cases for each 10% interval to the total number of merging vehicles as an evaluation index. The results for each ramp are shown in Figure 6.
As shown in the figure, the risky incidents for ramp A are distributed between 10% and 40% and at 60% of the merging position and display a high percentage. On the other hand, the distribution of the risky incidents for ramp B is wider than that for the other ramps, but the values are somewhat lower than those for ramp A, with the exception of the downstream results. For ramp C, the risky incidents are concentrated around the middle part of the merging section and the values are slightly lower than those for the other ramps.

4 Statistical Analysis of the Risky Merging Behaviors

4.1 Concept of Estimation of Risky Merging Situations at a Ramp

We focus on the traffic conflicts between a merging vehicle and the forward and/or rearward vehicles in the lane adjacent to the merging section. We analyze the relationship among the risky merging phenomena, surrounding traffic situation, and road structures. We determine whether the merging behavior is safe by the sign of the PICUD value as described above and perform a discriminant analyses to clarify the influencing factors. The traffic conflicts between the merging and main lane vehicles at a ramp comprise three cases: (1) the conflict between a merging vehicle and a leading vehicle in the adjacent main lane, (2) the conflict between a merging vehicle and a following vehicle in the adjacent main lane, and (3) the conflict among a merging vehicle, a leading vehicle, and a following vehicle in the adjacent main lane. Considering this, we develop three linear discriminant models as shown in Equation 2 for estimating the risky merging phenomena. Model 1 represents the case that a leading and a following vehicle exist in the main lane during a merging movement. Model 2 represents the case that either a leading or a following vehicle exists in the main lane during a merging movement, or Model 3 represents the consolidated data of both models.

\[
y = b_0 + b_1 x_1 + b_2 x_2 + \cdots + b_i x_i
\]

where

- \( y \): Discriminant score
- \( b_0 \): Constant
- \( b_i \): Estimated coefficient for explanatory variable \( x_i \)
- \( x_i \): Explanatory variables

4.2 Discriminant Analyses of Parameter Estimation Results

The discriminant analysis of the parameter estimation results for the three models described above is shown in Tables 2, 3, and 4.

For Model 1, it is found that there are two safe factors (blue shaded area) and two unsafe factors (red shaded area; Table 2).

It is shown that for a center-ramp, a merging starting position of 50% to 60% of the merging section relates to a safe situation. It is considered that drivers find it easy to merge at the middle of the merging section. Even during heavy vehicle traffic, it is a safe situation. We can infer that if the percentage of heavy vehicle traffic is high, the inter-vehicular distance in the main lane increases. On the other hand, both the traffic volume of the main lane and the type of the merging vehicle are unsafe factors. If the traffic volume of the main lane increases, the inter-vehicular distance decreases. Therefore, it is a logical result. If the leading merging vehicle is a heavy vehicle, it is considered that confirming the surrounding traffic situation is difficult owing to the existence of a heavy vehicle or a merging vehicle cannot accelerate adequately owing to the slower leading traffic.
For Model 2, it is found that there are two safe factors (blue shaded area) and four unsafe factors (red shaded area; Table 3). For a center-ramp, a merging starting position of 50% to 60% of the merging section relates to a safe situation as well as the result of Table 3; the situation in which a vehicle only exists downstream of the main lane when it tries to merge is also a safe situation. This means the speed of the vehicle that exists downstream of the main lane is greater than that of the merging vehicle, and the PICUD value tends to be positive. On the other hand, the higher the lane usage rate of the adjacent lane and the traffic volume of the main lane, the greater the traffic conflict risk at the ramps. In addition, a side-ramp with a merging starting position of 30 to 40% of the merging section is an unsafe situation. It is considered that drivers that merge at 30% to 40% of the merging section of the side-ramp structure tend to apply insufficient acceleration, thus leading to unsafe merging phenomena. Moreover, a heavy merging vehicle could also lead to unsafe phenomena. It is thought that heavy vehicles cannot sufficiently accelerate at a merging section.

Table 3 Parameter estimation for Model 2
(Significant probability ***: p<0.01, **:p<0.05, *:p<0.10)
For Model 3, it is revealed that there are two safe factors (blue shaded area) and three unsafe factors (red shaded area; Table 4). The explanatory variables are mostly common with those for Model 1 and Model 2.

In the next section, on the basis of sensitivity analyses of a developed model, we discuss the improvement in the quality of service at a ramp section from the viewpoint of reducing risky phenomena occurrence.

Table 4 Parameter estimation for Model 3
(Significant probability ***: p<0.01, **:p<0.05, *:p<0.10)

<table>
<thead>
<tr>
<th>Explanatory Variables</th>
<th>Standardized Coefficient</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combination dummy variable of side-ramp structure and merging starting position</td>
<td></td>
<td>0.2773**</td>
</tr>
<tr>
<td>[if the merging section is side-ramp and the merging starting position is from 30 to 40% of merging section: 1, others: 0]</td>
<td></td>
<td>1.2295</td>
</tr>
<tr>
<td>Lane usage rate of adjacent lane</td>
<td>0.3452***</td>
<td>9.0162</td>
</tr>
<tr>
<td>Traffic volume of main laneveh/min</td>
<td>0.6786***</td>
<td>0.0796</td>
</tr>
<tr>
<td>Percentage of heavy vehicle traffic</td>
<td>-0.2914**</td>
<td>-4.4661</td>
</tr>
<tr>
<td>Combination dummy variable of center-ramp structure and merging starting position</td>
<td></td>
<td>-0.3351***</td>
</tr>
<tr>
<td>[if the merging section is center-ramp and the merging starting position is from 50 to 60% of merging section: 1, others: 0]</td>
<td></td>
<td>-1.0840</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hito ratio</th>
<th>Safe</th>
<th>Unsafe</th>
<th>Total</th>
<th>Number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>67.4%</td>
<td>74.0%</td>
<td>71.7%</td>
<td>374</td>
</tr>
</tbody>
</table>

4.3 QOS Improvement at Ramp Section through Sensitivity Analysis

We attempt to evaluate the reduction in risky phenomena occurrence and discuss improvement in the QOS at the ramp section using Model 3. We performed three types of sensitivity analyses by using the change in the traffic volume of the main lane, the change in lane usage rate for the main lane, and the change in the merging starting position as policy variables. The results of the sensitivity analyses are shown in Figures 7, 8, and 9. We calculated the probability of risky merging movement for each vehicle and aggregated the percentage of risky merging phenomena for all data. We estimated the current situation and then changed the policy variables one by one.

Figure 7 shows that the percentage of risky merging phenomena reduces with the traffic volume of the main lane and a decrease of 6 vehicles/min in the traffic volume of the main lane causes a 10% improvement in the situation. However, it can be said that the probability of a decrease of 6 vehicles is low because the number indicates one-quarter of the total volume of the adjacent main lane.

Figure 8 reveals that the percentage of risky merging phenomena reduces with the lane usage rate for the main lane and a decrease of almost 3% in the lane usage rate results in a 10% improvement in the situation. We can consider this change to be more realistic than the change in traffic volume. The change in the lane usage rate can be achieved by appropriate indicators for drivers at the upstream section.

Figure 9 shows that the percentage of risky phenomena occurrence is reduced when the merging starting position changes downstream, and an increase in the merging starting position by 20% achieves an effect of 10% improvement in the situation. It can be thought that the change in the merging starting position is brought about by indicators for drivers of merging vehicles. For example, the recommended merging starting position and the merging starting position to be avoided can be indicated by different pavement colors.
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Figure 7 Sensitivity analysis for traffic volume of main lane

Figure 8 Sensitivity analysis for lane usage rate of adjacent main lane

Figure 9 Sensitivity analysis for merging starting position
5 Conclusion

We estimated collision risk by using a surrogate safety measure and discussed the quality of service perceived by drivers at merging sections of an urban expressway in Japan. First, to elucidate collision risk occurrences at merging sections, we analyzed the collision risk between a merging vehicle and a main lane vehicle by using the Possibility Index for Collision with Urgent Deceleration (PICUD). Second, we performed discriminant analyses of the PICUD estimation results to reveal the factors influencing collision risk at each merging section for several conflict patterns.

The interesting findings in this research are as follows:
- For the conflict among a merging vehicle, a leading vehicle, and a following vehicle in the adjacent main lane, a merging starting position of 50% to 60% of the merging section relates to a safe situation at a center-ramp. In addition, it is found that the higher percentage of heavy vehicle traffic, the safer situation. On the other hand, both the traffic volume of the main lane and the type of the merging vehicle are unsafe factors.
- For the case that either a leading or a following vehicle exists in the main lane during a merging movement, it is found that a merging starting position of 50% to 60% of the merging section also relates to a safe situation at a center-ramp; the situation in which a vehicle only exists downstream of the main lane when it tries to merge is also a safe situation. On the other hand, the higher the lane usage rate of the adjacent lane and the traffic volume of the main lane, the greater the traffic conflict risk at the ramps. In addition, a side-ramp with a merging starting position of 30 to 40% of the merging section is an unsafe situation.
- By the sensitivity analyses, it is revealed that the percentage of risky merging phenomena reduces with the lane usage rate for the main lane and a decrease of almost 3% in the lane usage rate results in a 10% improvement in the situation. In addition, it is also clarified that the percentage of risky phenomena occurrence is reduced when the merging starting position changes downstream, and an increase in the merging starting position by 20% achieves an effect of 10% improvement in the current situation. That is, it is expected that the quality of service at ramps are improved by conducting these countermeasures such as information provision at upstream or colored pavement for recommended merging starting position.

As future works, we try to develop traffic simulator with these discriminant models and estimate the effect of some countermeasures to improve quality of service at merging section in detail.

References

Merging Areas, Infrastructure planning review, No.1, 67-74.