Modeling Speed Adjustment Behavior of Merging Vehicles at Urban Expressway Merging Sections

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Abstract

This paper modeled speed adjustment behavior of merging vehicles by using video data collected at two merging sections on urban expressway in Nagoya City, Japan. The results showed that the longer acceleration lane results in a higher acceleration rate of merging vehicles. And the denser mainline traffic causes a lower that of merging vehicles. In addition, the leading and following time to collision ($TTC_L$ and $TTC_F$) were adopted as variables. It is found that if $TTC_L$ is negative, merging vehicles increase their acceleration rate. By contrast, if $TTC_L$ becomes positive and the collision can happen, merging vehicles tend to reduce acceleration rate to avoid the collision with leading mainline vehicles. In case of $TTC_F$, the positive signs of coefficients indicate that when following mainline vehicles run faster than merging vehicles, they increase their acceleration rate to avoid collision with following mainline vehicles. Furthermore, the validation results suggest a promising applicability of the developed models.

Keywords: Acceleration; deceleration; gap choice; traffic conditions; acceleration lane length

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1. Introduction

Expressway merging sections, which are designed to allow vehicles coming from a ramp to smoothly merge into the mainline, play as important nodes of expressway network. Their performances significantly affect the performance of the whole network. Therefore, the operational performance of these sections has been regarded as an important concern. Recently, traffic simulators e.g. AIMSUN, VISSIM, PARAMICS, etc., are considered as effective tools to evaluate the performance of facilities including merging sections. It is worth mentioning that, in order to reasonably evaluate the performance of merging sections, it is very important to take into account of various influencing factors on driver behavior before implementing it into the simulation models. However, the existing simulation models cannot precisely represent driver behavior under various influencing factors such as traffic conditions, geometry, and individual interactions between merging and mainline vehicles. To cover this gap, a research project has been carried out to develop several driver behavior models which can reasonably represent the whole maneuvers of merging and mainline vehicles. Then, the developed models will be incorporated into a traffic simulator to evaluate the performance of merging sections.

As a part of this research project, this paper aims at modeling the speed adjustment behavior (acceleration/deceleration) of merging vehicles by using video data. The video data were collected at two urban expressway merging sections in Nagoya City, Japan, covering not only uncongested regime but also congested regime of mainline traffic. Note that at the study sites, acceleration lanes were extended in 2011. Moreover, during the extension of these sections, the acceleration lanes were slightly shortened because of construction work. Hence, the video data taken during three periods of extension, which cover different acceleration lane lengths and mainline traffic conditions, supply this study a good database.

2. Literature reviews

Historically, the American Association of State Highway and Transportation Officials (AASHTO) has suggested that the acceleration lane length is based on ramp vehicle acceleration performance. The acceleration performance of vehicles in the acceleration lane was adopted from very old study in the late 1930's. However, its assumption that drivers can freely accelerate without any interaction with mainline vehicles is not realistic.

Michaels and Fazio (1989) found that there is a decline in speed between successive accelerations when merging drivers are searching gap. This implies that mainline vehicles have a pronounced influence on merging vehicle acceleration behavior and that impacts cannot be excluded from the formulation of merging vehicle acceleration. Kou and Machemenhl (1997) reported that when merging vehicles are running in the acceleration lane, they interact with mainline vehicles and with other merging vehicles as well. Consequently, their acceleration characteristics cannot be modeled by simply assuming no other vehicles exist. In order to consider these interactions, they adopted the concepts of car-following for modeling acceleration/deceleration behavior of merging vehicles.

Although Kou and Machemenhl's model is capable of representing the interaction of merging and mainline vehicles, its application is limited to uncongested conditions. Sarvi et al. (2002) overcame this limitation by using data collected under congested conditions on Tokyo Metropolitan Expressway and used the same idea to model acceleration behavior of merging vehicles. It is highlighted that both models of Kou and Machemenhl (1997) and Sarvi et al. (2002) cannot represent how the gap searching and gap acceptance affect the acceleration/deceleration behavior. However, the gap searching and gap acceptance might have significant impacts on the acceleration characteristics of merging vehicles.

Chu et al. (2013) modeled the gap choice behavior by classifying merging choice into three patterns: “direct-“, “chase-“ and “yield-merging” depending on the interactions between merging and mainline vehicles at assumed decision point. The present paper is the continuation of this work in order to develop behavior models which can represent the whole merging maneuvers. Then, developed models will be incorporated in a traffic simulator for a reasonable evaluation of the operational performance of merging sections.

3. Study sites, data collection and processing
3.1. Study sites and data collection

This paper utilizes the video data that were collected at Horita and Takatsuji entrances. These entrances are located on urban expressway route No. 3 in Nagoya City, Japan (left-hand traffic). As shown in Fig. 1, both of the sections are positioned on the middle of carriageway and acceleration lanes were extended in October 2011 as a trial to lighten traffic congestion. In addition, during the process of extending the sections, the acceleration lanes were slightly shortened (-30m) because of construction work. This study denotes the situations of before, during and after the extension of acceleration lanes as “before”, “during” and “after”, respectively.

In order to reduce errors while tracking vehicle trajectories, video cameras were positioned on the top of high buildings located close to the merging sections. Video data were collected at both Horita and Takatsuji entrances, covering situations of not only “before” and “after” but also “during” in various times of the day and days of the week. This enables to observe different mainline traffic conditions including both congested and uncongested regimes.

It is worth noting that since the different lengths of acceleration lane were observed at the same merging section, the characteristics of drivers such as driver’s population, percentage of aggressive drivers are expected to be similar for “before”, “during” and “after” situations. Table 1 summaries the observation dates, the duration of survey and the mainline traffic situation.
Table 1. Video survey periods and mainline traffic conditions

<table>
<thead>
<tr>
<th>Merging Section</th>
<th>Situation</th>
<th>Acceleration lane length L (m)</th>
<th>Survey date</th>
<th>Day</th>
<th>Survey time</th>
<th>Mainline flow rate (veh/h-2lane) (Min-Max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horita Entrance</td>
<td>Before</td>
<td>170</td>
<td>09/16/2005</td>
<td>Friday</td>
<td>14:00 - 17:00</td>
<td>1735 - 3158</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>07/26/2011</td>
<td>Tuesday</td>
<td>06:00 - 10:50</td>
<td>588 - 3240</td>
</tr>
<tr>
<td></td>
<td>During</td>
<td>200</td>
<td>07/10/2011</td>
<td>Saturday</td>
<td>05:45 - 09:00</td>
<td>432 - 2232</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>11/10/2011</td>
<td>Thursday</td>
<td>14:00 - 18:00</td>
<td>2064 - 3348</td>
</tr>
<tr>
<td></td>
<td>After</td>
<td>280</td>
<td>01/18/2005</td>
<td>Tuesday</td>
<td>08:00 - 10:00</td>
<td>2650 - 3325</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>08/02/2011</td>
<td>Tuesday</td>
<td>09:00 - 11:00</td>
<td>2400 - 3072</td>
</tr>
<tr>
<td>Takatsui Entrance</td>
<td>During</td>
<td>200</td>
<td>08/06/2011</td>
<td>Saturday</td>
<td>12:00 - 15:00</td>
<td>1500 - 2316</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>01/10/2011</td>
<td>Thursday</td>
<td>14:00 - 18:00</td>
<td>1800 - 2820</td>
</tr>
<tr>
<td></td>
<td>After</td>
<td>365</td>
<td>01/13/2012</td>
<td>Friday</td>
<td>06:45 - 09:30</td>
<td>2154 - 3242</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>01/21/2012</td>
<td>Saturday</td>
<td>08:00 - 12:15</td>
<td>1584 - 2496</td>
</tr>
</tbody>
</table>

3.2. Vehicle trajectory extraction

Trajectories of free merging vehicles were extracted from video data by using an image processing system TrafficAnalyzer (Suzuki and Nakamura, 2006) as shown in Fig. 2. A free merging vehicle is defined as the merging vehicle that does not face any other merging vehicles on the acceleration lane at the moment of passing physical-nose. The position and timing of each vehicle were manually extracted every 1.0 second. Afterwards, the Kalman Smoothing function was used to smoothen vehicle trajectories by every 0.1 seconds. The point where the right-rear wheel is touching the ground is defined as the reference observation point for all vehicles. By taking into account of the dimension of each vehicle, the observed trajectories based on the right-rear wheel were transformed to the trajectories which correspond to the center of the vehicles.
From the vehicle trajectories, the position, speed and acceleration/deceleration rate of not only merging vehicles but also their corresponding leading and following mainline vehicles at the time $t$ are extracted, as detailed in Fig. 3. It is assumed that merging vehicles start to adjust their speed when they enter the physical-nose (starting observation point) until they complete lane changing (ending observation point). After the lane changing, their speed adjustment can be considered as a normal car-following situation. The point that merging vehicle completes lane changing is defined as the position where the right-rear wheel of merging vehicle touches the dashed marking line.

$$DM(t)$$

Starting observation point (physical-nose)

$$XM(t)$$

$$VF(t)$$

$$XL(t)$$

$$VM(t)$$

$$VL(t)$$

Fig. 3. Data extraction

3.3. Density data collection

Density data were collected to consider the effects of mainline traffic conditions. It is assumed that a merging vehicle starts to be influenced by vehicles on median lane within the length of acceleration lane (hereafter “influenced area”) when it reaches the physical-nose as displayed in Fig. 4 a). It is important to mention that the density is a function of time and the density within the influenced area changes as the merging vehicle moves from the physical-nose until completing its lane-changing. However, to simplify, this paper assumes that the density in this area is unchanged. Later on, the density of mainline ($k$, veh/km/lane) is computed by the following Equation.

$$k = 1000 \frac{N}{L}$$

Where $N$ is number of mainline vehicles on the median lane within the influenced area at the moment merging vehicle reaches the physical-nose and $L$ is the acceleration lane length (m).
3.4. Classifications of gap choice

As explained in Chu et al. 2013, the choices of merging vehicles were divided into “direct-”, “chase-” and “yield-merging” depending on interactions between merging and mainline vehicles at the decision point. The classifications are represented in Fig. 4 b). The present paper adopts these classifications to take into account of gap choice behavior for modelling the speed adjustment behavior.

A total of 578 pair-trajectory data of merging and corresponding mainline vehicles was collected. Table 2 presents the total sample size of merging maneuvers at both study sites for types of gap choice. Note that only passenger cars are considered since heavy vehicle ratio is very low (less than 5%).

<table>
<thead>
<tr>
<th>Merging section</th>
<th>Situation</th>
<th>Acceleration lane length (m)</th>
<th>Merging choice</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Direct</td>
<td>Chase</td>
</tr>
<tr>
<td>Horita Entrance</td>
<td>During</td>
<td>170</td>
<td>82</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Before</td>
<td>200</td>
<td>33</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>After</td>
<td>280</td>
<td>77</td>
<td>6</td>
</tr>
<tr>
<td>Takatsuji Entrance</td>
<td>During</td>
<td>170</td>
<td>62</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Before</td>
<td>200</td>
<td>32</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>After</td>
<td>365</td>
<td>90</td>
<td>9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>396</td>
<td>127</td>
</tr>
</tbody>
</table>

4. Methodology

4.1. Model structure

As illustrated in Fig. 5, when a merging vehicle comes to physical-nose, it will search an acceptable gap and choose an intended gap to merge. Then it starts to adjust its speed based on the mainline traffic. At assumed decision point, it will check again the intended gap and decide whether to directly merge into that gap or yield/chase the gap. The assumed decision point is defined as 30m downstream from physical-nose. The details of gap choice model and assumed decision point can be seen in Chu et al. (2013). The present paper continues the works of Chu et al. (2013) by considering the speed adjustment behavior as a result of gap choice model.

4.2. Model formulation

Kou and Machemenhl (1997) as well as Sarvi et al. (2002) have suggested that, the acceleration performance of merging vehicles on acceleration lanes is much more complicated than what the car-following model can describe. It is because more factors need to be considered such as the existence of following mainline vehicles. In addition, merging vehicles have to finish their lane changing before the end of acceleration lane. They, therefore, need to adjust their speed depending on the distance from their current position to the end of acceleration lane. Essentially, the central basic for modeling ramp vehicle acceleration-deceleration is different from that of car-following model. Nevertheless, the fundamental concepts of the Gazis-Herman-Rothery (GHR) car-following model can be appropriately adopted. Generally, in GHR model the acceleration of following vehicle is assumed to be proportional with relative speed and inversion of relative position between the following vehicle and the leading vehicle. This research still follows the assumption of GHR model; however, the concept of time to collision (TTC) proposed by Allen et al. (1978), is adopted instead of relative speed and relative space. It is expected that adopting the definition of TTC can explain the reaction of merging vehicles to mainline vehicles from safety point of view. Similar idea can be found in studies of Van Winsum and Heino (1996) as well as Van Winsum and Brouwer (1997), which introduced TTC as a variable to study breaking response of drivers in following vehicles. Together with TTC, new
variables, i.e. distance to the end of acceleration lane, length of acceleration lane and traffic density are added. The multiple linear model is adopted with explanatory variables as represented in Equation (2):

\[
\begin{align*}
    a(t+T) &= \beta_0 + \beta_1 a(t) + \beta_2 V_M(t) + \beta_3 \frac{V_{F}(t) - V_{M}(t)}{X_{M}(t) - X_{F}(t)} + \beta_4 \frac{V_{M}(t) - V_{L}(t)}{X_{M}(t) - X_{L}(t)} + \beta_5 \frac{1}{D_{M}(t)} + \beta_6 L + \beta_7 k + \epsilon_{(t+T)} \\
    &= \beta_0 + \beta_1 a(t) + \beta_2 V_M(t) + \beta_3 \frac{1}{TTC_{F}(t)} + \beta_4 \frac{1}{TTC_{L}(t)} + \beta_5 \frac{1}{D_{M}(t)} + \beta_6 L + \beta_7 k + \epsilon_{(t+T)} 
\end{align*}
\]  

(2)

Where, \(a(t)\) and \(a(t+T)\) are acceleration rate of merging vehicle at time \(t\) and \(t+T\), \((\text{m/s}^2)\). \(T\) is the reaction time of driver (s). As previously defined in Fig. 3., \(V_M(t)\), \(V_F(t)\), \(V_L(t)\) and \(X_M(t)\), \(X_F(t)\), \(X_L(t)\) are speed \((\text{km/h})\) and position \((\text{m})\) of merging vehicle, following and leading mainline vehicles at time \(t\), respectively. \(D_M(t)\) is the distance from the position of merging vehicle at time \(t\) to the end of acceleration lane, \((\text{m})\). \(L\) is the length of acceleration lane length \((\text{m})\). \(k\) is the density of median lane as aforementioned. \(TTC_F(t)\) and \(TTC_L(t)\) are the time to collision between merging and following/leading mainline vehicles. \(\beta_i\) is parameter to be estimated. And \(\epsilon_{(t+T)}\) is the error term.

5. Results and discussion

5.1. Acceleration characteristics of merging vehicles

Fig. 6 shows speed and acceleration profiles of merging vehicles at Horita entrance in “during” situation with an estimated time of every 0.1 second.
Inspection of Fig. 6(a) indicates that under free-flow of mainline, merging vehicles don’t have to interact with mainline vehicles and they keep accelerating. Their behavior is different compared to merging vehicles that face with mainline vehicles. Comparing Figs. 6(a) and(b) shows that, although initial speeds (at \( t = 0, \) physical-nose) of merging vehicles under low density condition are approximately closed to that of merging vehicles under free-flow conditions, merging vehicles cannot keep increasing their speeds. This result confirms previous discussion that when mainline vehicles exist, merging vehicles cannot avoid influences of mainline vehicles. They have to adjust their speed and acceleration rate to safely position themselves in the accepted gap. In case of high density condition, as detailed in Fig. 6(c), merging vehicles firstly have to decelerate. Afterwards they reduce their deceleration rate and then accelerate to merge into the mainline. It could be inferred that under high density condition, mainline traffic is almost be congested and the speeds of mainline vehicles are quite low. Therefore, merging vehicles usually enter physical-nose with higher speed compared to that of mainline vehicles. In order to find an acceptable gap for a safe merge, they have to decelerate to close speed differences between them and mainline vehicles.

5.2. Estimation results of speed adjustment models

One of the most important parameters for the model is the reaction time (\( T \)) of driver. In reality, the reaction time might be affected by many factors such as age, mental condition, visibility, weather conditions, roadway geometry, vehicle characteristics, vehicle speed, and so on. For instance, older drivers are expected to have longer reaction times. Poor visibility increases driving difficulty and drivers are expected to be more alert and might lead to a reduction in reaction time. Many studies have shown that the reaction time of driver ranges from 0.4 to 2.7s with the mean around 0.7 to 1.3s. (Johansson and Rummer, 1971; Magister et al., 2005; Fambro et al., 1998). In order to find best-fit models, the models were built for different reaction times of 0.5, 1 and 1.5s. It is found that for all cases, the reaction time of 1 second showed the best-fit with highest R-square.

The estimation results of models with reaction time of 1s are shown in Table 3. It is clear that the current acceleration rate and speed of merging vehicles significantly affect the acceleration rate that merging vehicles are going to choose. In addition, the distance from current position of merging vehicles to the end of acceleration lane is also a significant variable for all cases. When merging vehicles approach to the end of acceleration lane, they adopt higher acceleration rate if they are accelerating and, on the contrary, they adopt lower deceleration rate if they are decelerating. Moreover, acceleration lane length and density significantly affect the acceleration/deceleration characteristics of merging vehicles. The longer acceleration lane results in a higher acceleration rate of merging vehicles, and the denser mainline traffic condition exhibits lower that of merging vehicles.

Regarding the time to collision, the signs of models are logical. The leading time to collision (\( TTC_L \)) is more significant variable compared to following time to collision (\( TTC_F \)) except model 3 (yield-merging). If \( TTC_L \) is negative and the collision is not possible; merging vehicles increase their acceleration rate. By contrast, if \( TTC_L \) becomes positive and the collision can happen, merging vehicles tend to reduce acceleration rate to avoid the collision with leading mainline vehicles. In case of following time to collision (\( TTC_F \)), the positive signs of coefficients indicate that when following mainline vehicles run faster than merging vehicles, they increase their acceleration rate to avoid collision with following mainline vehicles.
Table 3. The estimation result of speed adjustment model

<table>
<thead>
<tr>
<th>Dependent variables</th>
<th>Model 1 (Direct)</th>
<th>Model 2 (Chase)</th>
<th>Model 3 (Yield)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.15 (1.6)</td>
<td>-0.031 (-2.3)</td>
<td>0.27 (1.5)</td>
</tr>
<tr>
<td>Acceleration rate of merging vehicle $a_{i0}$ (m/s²)</td>
<td>0.67 (25)</td>
<td>0.49 (14)</td>
<td>0.58 (8.2)</td>
</tr>
<tr>
<td>Speed of merging vehicle $V_{M0}$ (m/s)</td>
<td>-0.016 (-5.6)</td>
<td>-0.017 (-5.5)</td>
<td>-0.016 (-2.2)</td>
</tr>
<tr>
<td>Reciprocal of following time to collision $1/TTC_{i0}$ (1/s)</td>
<td>0.013 (1.9)</td>
<td>0.0019 (1.5)</td>
<td>0.024 (2.4)</td>
</tr>
<tr>
<td>Reciprocal of leading time to collision $1/TTC_{i0}$ (1/s)</td>
<td>-0.0011 (-2.1)</td>
<td>-0.0016 (-2.4)</td>
<td>-0.0022 (-1.1)</td>
</tr>
<tr>
<td>Reciprocal of distance to the end of acceleration $1/D_{i0}$ (1/m)</td>
<td>9.6 (2.3)</td>
<td>4.2 (2.1)</td>
<td>8.9 (2.4)</td>
</tr>
<tr>
<td>Acceleration lane length (m)</td>
<td>0.0013 (3.9)</td>
<td>0.0012 (2.8)</td>
<td>0.0014 (2.1)</td>
</tr>
<tr>
<td>Density $k$ (veh/lane/km)</td>
<td>-0.0040 (2.9)</td>
<td>-0.0015 (-3.2)</td>
<td>-0.0041 (2.5)</td>
</tr>
<tr>
<td>R square</td>
<td>0.63</td>
<td>0.68</td>
<td>0.64</td>
</tr>
<tr>
<td>Sample size (data point of every 1 second)</td>
<td>4150</td>
<td>2432</td>
<td>320</td>
</tr>
</tbody>
</table>

5.3. Model validation

To validate the model, the acceleration and speed deduced from developed models are compared with the observed ones. The observed acceleration and speed are different from data set for modeling part. Initial values of estimated speed $V_{i0}$ and acceleration $a_{i0}$ is given the same as that of the observed ones. Here, $t_0$ is the moment when merging vehicles pass the position of physical-nose. Then, for every reaction time $T = 1$s, the acceleration rate at time $t + T$ $(a_{i(t+T)})$ is estimated by Equation (2). In addition, the speed at time $t + T$ $(V_{i(t+T)})$ is calculated based on the kinematic formula as shown in Equation (3).

$$V_{i(t+T)} = V_{i(t)} + a_{i(t)}T$$  \hspace{1cm} (3)

The estimated acceleration and speed are updated every 1s until the moment when merging vehicles complete their merging. It is assumed that the complete merging moment is the same for estimated and observed trajectories. Figs. 7 and 8 show the results of the validation for all models. It is concluded that the developed models give a promising applicability in reproducing the acceleration and speed profiles of merging vehicles.

![Comparison of estimated and observed acceleration rate](image-url)
6. Conclusions

The merging maneuver is a complicated process that involves gap searching, speed adjustment behavior and lane changing. By using empirical data collected at urban expressway merging sections in Nagoya City, Japan, this paper proposes a methodology to model the speed adjustment behavior taking into account of gap choice behavior, mainline traffic conditions and the geometry of merging section.

Generally, it is concluded that the acceleration/deceleration characteristics of merging vehicles are varied depending on the mainline traffic conditions and results of gap choice behavior. The longer acceleration lane results in a higher acceleration rate of merging vehicles, and the denser mainline traffic condition exhibits lower that of merging vehicles. The concept of time to collision (TTC) was adopted as an explanatory variable to model the speed adjustment behavior. The results showed that merging vehicles always tend to keep a safe condition to both leading and following mainline vehicles when finding/accepting a gap and making a lane changing. However, the reaction of merging vehicles to leading and following mainline vehicles is different due to mainline traffic conditions and results of gap choice. It is found that if $\text{TTC}_L$ is negative, merging vehicles increase their acceleration rate. By contrast, if $\text{TTC}_L$ becomes positive and the collision can happen, merging vehicles tend to reduce acceleration rate to avoid the collision with leading mainline vehicles. In case of $\text{TTC}_F$, the positive signs of coefficients indicate that when following mainline vehicles run faster than merging vehicles, they increase their acceleration rate to avoid collision with following mainline vehicles.

The models were validated and the results indicate that they are able of reproducing the acceleration and speed profiles of merging vehicles in different mainline traffic conditions and gap choice. The proposed models are originally intended to be incorporated into an algorithm to reproduce the vehicle maneuvers inside a microscopic simulation environment for estimations of merging section performance.

Even though the applicability of developed models is promising, the models still have some limitations. In this paper, the models are limited to merging vehicles, which did not face any other merging vehicles in front of them while entering the physical-nose. Therefore, collecting following merging vehicles, which face with other merging vehicles ahead, is necessary to improve the developed models. In addition, the developed models are limited to the acceleration lanes located in the middle of expressway carriageways (right-hand-side entrances) with available range of acceleration lane lengths at study sites. Thus, it is very important to collect the data of left-hand-side entrances with more available range of acceleration lane lengths in order to generalize the developed model. On the other hand, other driver behavior e.g. the merging position and merging speed as the results of gap choice and speed adjustment behavior or the car-following model of mainline vehicles, which considers the interaction with merging vehicles, need to be further investigated.

References


