Lane-changing gap acceptance model for freeway merging in simulation

Jin-Tae Kim, Joonhyon Kim, and Myungsoon Chang

Abstract: Existing techniques for microscopic simulation of lane changes utilize a single critical gap for a single vehicle. Freeway merging areas have been among the most difficult aspects of simulations due to the wide variety of merging behaviors in these areas. This paper proposes a gap acceptance model developed to update the size of the critical trailing gap for a merging vehicle during simulation based on the location of the vehicle in an acceleration lane. It also considers the relative speed and critical leading gap. Sets of critical trailing gap values for various situations are computed. The outputs from the microscopic simulations utilizing the proposed model were compared with field data, producing strong statistical evidence that the simulation results and field data were significantly comparable.

Key words: lane changing, driver behavior, gap acceptance, freeway, simulation.

Résumé : Les techniques existantes de simulation microscopique des changements de voies utilisent un seul intervalle de sécurité pour un véhicule unique. Les zones de convergence des autoroutes ont été parmi les parties les plus difficiles à simuler en raison de la grande variété de comportements de convergence dans ces zones. Le présent article propose un modèle d'acceptation de l'espacement pour mettre à jour la dimension de l'espacement critique en arrière d'un véhicule en convergence durant une simulation basée sur la localisation du véhicule sur la voie d'accélération. Il considère aussi la vitesse relative et l'espacement critique en avant. Des ensembles de valeurs d'espacements critiques à l'arrière sont calculés pour diverses situations. Les résultats des simulations microscopiques utilisant le modèle proposé ont été comparés aux données de terrain, fournissant une forte preuve statistique que les résultats de simulation et les données de terrain sont très comparables.

Mots-clés : changement de voie, comportement des conducteurs, acceptation d'espace, autoroute, simulation.

[Traduit par la Rédaction]

1. Introduction

Congestion on freeway on-ramp sections often affects the operational condition of upstream traffic and has been recognized as an important issue in freeway management. Traffic engineers have developed various techniques for analyzing traffic performance in these sections. Among these techniques, microscopic simulation has been of central interest in recent decades because of its capacity for linking various types of freeway facilities and its ability to reflect the randomness of traffic effectively.

In current simulation techniques, drivers are generally classified into several types according to driving behavior. For example, the freeway simulation (FRESIM) model (Henry et al. 1997), developed by the Federal Highway Administration (FHWA) in the United States, delineates 10 different driver types by classifying parameters such as free-flow speed, maximum acceleration and deceleration rates, and critical gap size.

Traffic engineers have accepted that a driver's behavior depends on operational conditions on freeway facilities (Wattleworth et al. 1967; Kita 1993; Ahmed 1999; Wei et al. 2000). In current simulation techniques, however, the parameter values mentioned in the previous paragraph do not vary with driving conditions. Such methodologies are useful, but assume that drivers react in the same way to stimuli, no matter what the conditions.

This paper presents a study on drivers' gap acceptance behavior when merging onto a freeway. The authors hypothesized that the critical gap size of a merging vehicle depends on driving conditions. The introduction of parameters accounting for this variation into microscopic simulation could potentially help improve simulation accuracy.

The objective of the study is to analyze field data to confirm the validity of the hypothesis and to introduce a gap acceptance model accounting for the dynamic merging behavior described above. The model should reflect the structure of the current microscopic simulation techniques that utilize a set of different driver types. In this article, the "target lane" is the one that a vehicle merges into from an acceler-

Received 16 January 2007. Revision accepted 20 September 2007. Published on the NRC Research Press Web site at cjce.nrc.ca on 28 March 2008.

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Written discussion of this article is welcomed and will be received by the Editor until 31 July 2008.

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 doi:10.1139/L07-119

ation lane. To test the research hypothesis, the following test items were developed:

(1) Determination of the critical gap between a merging vehicle in an acceleration lane and a leading vehicle in a target lane.
(2) Determination of the critical gap between a merging vehicle in an acceleration lane and a trailing vehicle in a target lane.
(3) Verification of the range of speed differences between the merging vehicle in an acceleration lane and the trailing vehicle in a target lane.
(4) Determination of whether the driver's gap acceptance behavior changes at different locations in the acceleration lane and, if so, how.

Traditionally, three types of lane changing behavior have been defined: mandatory, discretionary, and anticipatory (Henry et al. 1997). A lane changing model for each of these types generally consists of three components: a decision model, a condition model, and a maneuver model. The scope of the study is limited to the condition model for mandatory lane changes.

"Mandatory lane change" refers to a lane change that a driver has to make to remain on the correct route or to avoid an obstacle, and includes avoiding the end of an acceleration lane in the merging area. "Discretionary lane change" refers to a lane change that a driver willingly makes to maintain his or her desired speed by passing a slower-moving vehicle. "Anticipated lane change" refers to a lane change that a driver willingly makes to avoid potential congestion downstream.

2. Background

Previous studies were reviewed to understand the current status of gap acceptance and lane change models for merging related to microscopic simulation. In the 1960s, Worrall et al. (1967) reported that total traffic volume on a mainline freeway was not a significant factor affecting a driver's decision to make a lane change for merging. They indicated, however, that it was significantly influenced by (the absolute value of) the relative speed between vehicles in acceleration and target lanes. (The relative speed is the difference of the speeds of vehicles.) Wattleworth et al. (1967) found that a vehicle's location in an acceleration lane significantly affected a driver's lane-changing behavior. They indicated that a driver tended to accept smaller gaps as the remaining distance to the end of an acceleration lane decreased and as the merging angle increased. Based on these findings, Drew (1969) explained driver's gap acceptance behavior with regression analyses, employing the shape and length of an acceleration lane and the merging angle as independent variables. He found that the critical gap of a merging vehicle became longer when the merging angle was larger.

In the 1980s, Michaels and Fazio (1989) proposed a model to estimate the merging location in an acceleration lane based on the traffic volume and angular velocity. The angular velocity is the rate of change of the angle between the merging vehicle in an acceleration lane and the trailing vehicle in a target lane. As the angular velocity data is, in practice, difficult to measure, their model is difficult to use in simulations. Gipps (1986) indicated that the preceding research dealt mostly with lane-changing condition models, but not with decision models. He developed a system for modeling decisions to change lanes, in which variables identified as affecting the decision are used as parameters in a microscopic simulation environment. In addition, Reilly et al. (1989) found from the field data that 60% of merging drivers conducted lane changes for merging when their relative speed was less than or equal to 8 km/h. In the 1990s, the American Association of State Highway and Transportation Officials (AASHTO) (AASHTO 1994) reported that merging took place when the relative speed was less than 8 km/h.

Kita (1993) developed a binary discrete choice model to explain a driver's gap acceptance decision procedure. He reported that critical gaps were determined by the relative speed between the vehicles in acceleration and target lanes, the density of a target lane when merging, and the remaining distance to the end of the acceleration lane. He reported that drivers tended to accept shorter gaps as the distance to the end of an acceleration lane decreased. Ahmed (1999) found, based on field data, that critical gaps followed a log-normal distribution. He indicated that the leading and trailing critical gaps in mandatory lane changes were smaller than those in discretionary lane changes.

Wei et al. (2000) investigated lane changes in an urban network, noting that most preceding studies were related to lane changes on freeways. They suggested that lane-changing behavior in urban networks should be categorized into three different types: mandatory, preemptive, and discretionary lane changes. "Preemptive lane change" refers to a lane change that a driver willingly makes for easier turning at downstream intersections rather than for a speed advantage. They proposed a set of the model structures for such lane changes. They reported that the critical leading and trailing gaps typically varied depending on the types of lane changes: the critical values of these gaps, in the case of mandatory lane changes, are less than those of discretionary lane changes.

Sultan et al. (2002) studied dynamic cut-in lane changes on a three-lane motorway, the M27 in the UK, by emphasizing the size of the critical trailing gap. They found that the critical gaps for cut-in lane changes were as low as 0.25 s, with a mean of 0.59 s, when merging into a faster lane. In addition, these became as low as 0.19 s, with a mean of 0.42 s, when the lane change was made into a slower lane. The results of their research support the findings of Wei et al.(2000) that these values are much lower than those of ordinary lane changes.

Interestingly, Toledo et al. (2003) reported that classification of lane changes as either mandatory or discretionary prohibits capturing the trade-offs between them. They proposed the integrated lane-changing discrete-choice model that allows joint evaluation of mandatory and discretionary lane changes. It uses a single critical gap value for both discretionary and mandatory lane changes and barely supports the previous findings that critical gaps vary depending on the types of lane changes.

Hidas (2005) introduced three different types of lane-change maneuvers for merging: free, forced, and cooperative lane changes. He proposed using either forced cut-in or cooperative lane changes for the cases when the merging vehicle is close enough to the end of the acceleration lane and that the predefined single critical gap was not suitable for possible merging. He reported that the results of microscopic simulation became positively comparable to the ones of macroscopic analysis when the concept of cooperative lane change was employed in simulation. However, he only considered the spacing gap, leaving room for improvement with the time gap concept.

Various computer-based simulation models utilize their own lane-change procedures. These models consider the acceptance risk (a function of maximum deceleration rate) of the trailing vehicle as the one of the merging conditions. Corridor simulation (CORSIM) (ITT Industries 1999) is one of the widely used microscopic simulation models in practice. It provides an optimistic performance of lane changes by arbitrarily using the minimum critical gap when a merging maneuver cannot be made due to congestion over a certain time period. The "Analysis of Road Traffic and Evaluation by Micro-Simulation" (ARTEMiS) (Hidas 2005) is the model that is capable of capturing the variation of merging behavior by utilizing cooperative lane change. It deals with spacing gaps for merging.

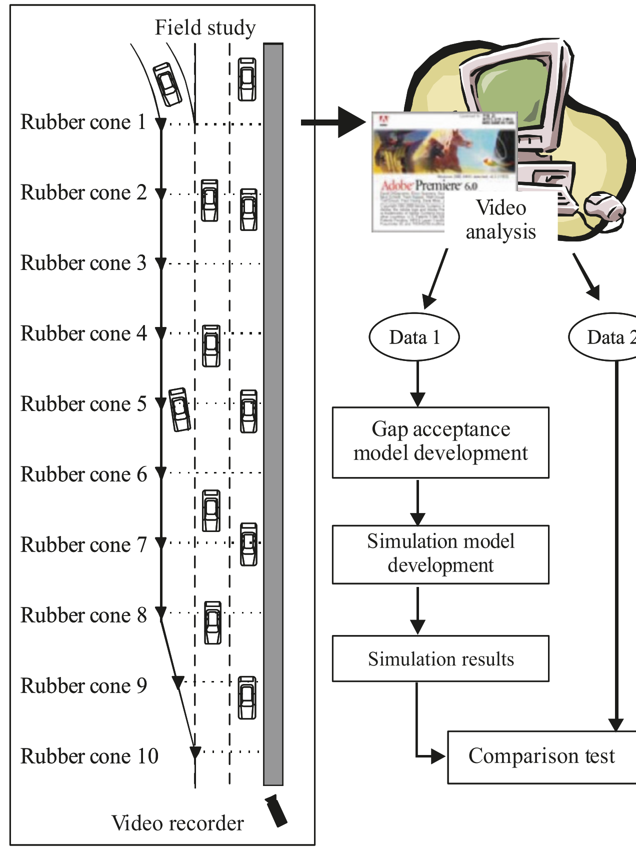
3. Data collection

Field data were collected for the study from two different freeway merging areas. The selected areas were the "Mokdong" (site A) and "Omok" (site B) freeway on-ramp areas in Seoul, Korea. These on-ramp sections satisfy favorable design conditions and utilize different lengths of acceleration lanes: 170 and 236 m, respectively. The speed limits and lane widths of both sections are 70 km/h and 3.5 m, respectively. The field data collection on both sections included two peak hours (0700–0900) and two off-peak hours (1000–1200). Figure 1 illustrates the study procedure, including the data collection method.

Digital video recorders were used to collect raw video-streaming data from both sites, and then the recorded data were reduced in the lab. The recorders were installed behind the median barrier so that drivers were unaware that they were being recorded. At each site, 10 rubber cones were uniformly placed along the shoulder of the acceleration lane to assist in measuring distance in the data reduction procedure. Data reduction was carried out by comparing a series of screen shots, recorded at the rate of 30 frames/s, with video image editing software.

Field data were extracted by referencing the moment that the front bumper of a merging vehicle in an acceleration lane hits the white lane marking on the side of the target lane. At that moment, the vehicles in the target lane immediately to the front and rear of the merging vehicles are referred to as the leading and trailing vehicles, respectively. The data extracted through a data reduction procedure include: (*i*) the leading gap between the merging and leading vehicles, (*ii*) the trailing gap between the merging and trailing vehicles, (*iii*) the location of the merge, (*iv*) the relative speed between the merging and trailing vehicles, and (*v*) the traffic density in the target lane. The density data were collected by counting the number of vehicles in the target lane in the section along the acceleration lane.

Fig. 1. Data collection and study procedure.



The critical gaps cannot be observed under free-flow conditions; therefore, the data should be collected when the target lane traffic density is high. Data was collected only when the gap between vehicles (leading and trailing) was no more than 6 s. When a gap was higher than 6 s, the observed condition was temporarily considered as a free-flow condition. No data was collected during such conditions.

The data collected from sites A and B were randomly divided into two groups for the study: data 1 and data 2. Data 1 and data 2 comprise 75% and 25% of the total data, respectively. Data 1 was used in the development of the proposed gap acceptance model, whereas data 2 was reserved for the validation test.

4. Data analysis

Field data in data 1 were analyzed prior to developing the model to verify parameter distributions required for the simulations and to understand patterns of driving behavior. Total traffic volume in the target lane varied from 1129 to 1851 vehicles per hour per lane (veh/h/l). Total traffic volume on the acceleration lane varied from 73 to 256 veh/h/l. Statistical analysis (which was conducted at a 95% confidence level) concluded that the speeds of merging vehicles were distributed normally with a mean of 60 km/h and a standard deviation of 10 km/h.

A set of additional statistical tests was performed to verify:

(1) whether the critical leading and trailing gaps found on a target lane need to be varied during simulation or can be treated as constant
(2) whether and how traffic density affects the distribution of lane changing locations along an acceleration lane
(3) whether and how the lengths of an acceleration lane affect the lane changing for merging
(4) whether and how the relative speeds between vehicles in the target and the acceleration lanes affect merging. The following subsections describe the results of these tests.

4.1. Leading and trailing gaps

The lane-changing model considers both critical leading and critical trailing gaps. It was hypothesized in this study that it would be advantageous if the critical gap was treated as a variable in simulation. This is because the critical gap would virtually change in congested conditions due to the change of the drivers' willingness to tense. The distributions of these leading and trailing gaps were analyzed to determine whether either one or both of these gaps should be treated as one or two variables, although the leading gap was already insignificantly treated in current practice. A previous study indicated that "the leader vehicle is usually a passive player in the lane change process" (Hidas 2005).

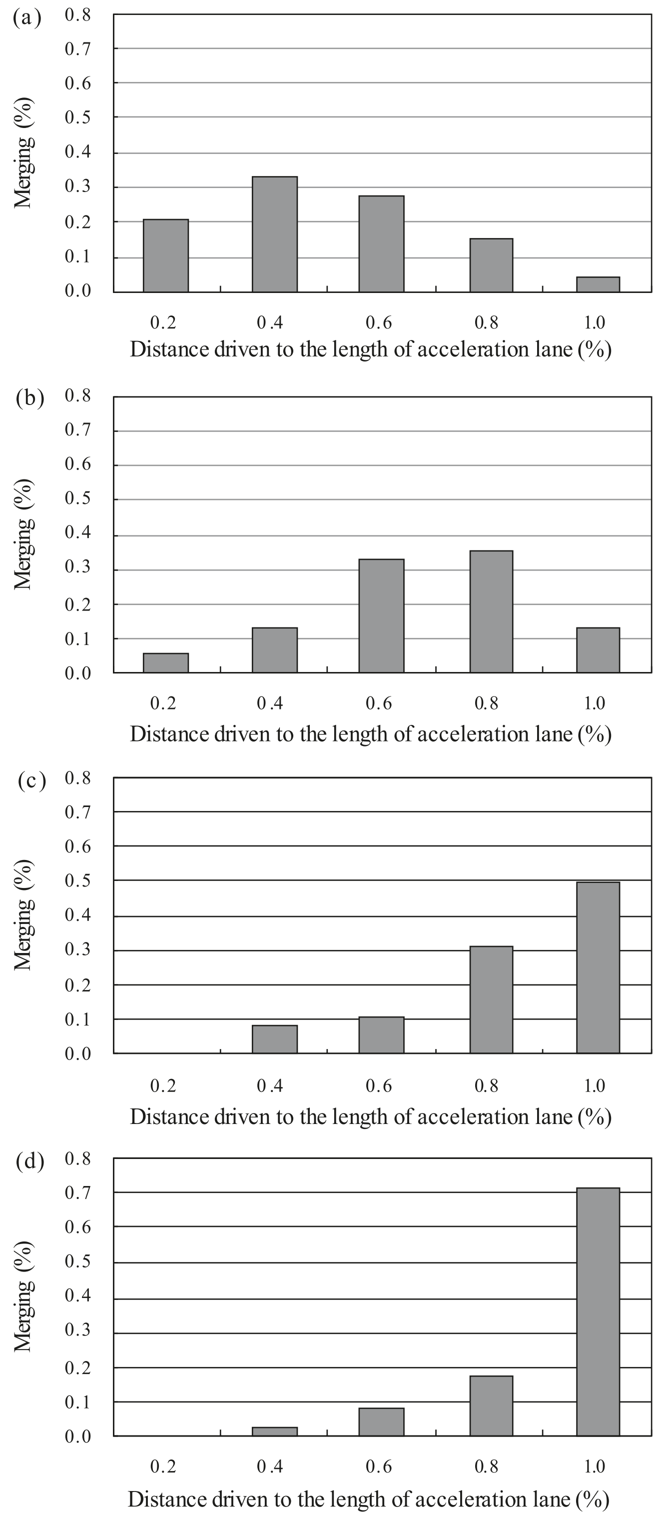
There would be no need to treat one of these gaps as a variable in simulation when its variation range is small. Conversely, it would be better to treat it as a variable if the value varies widely. This is because of the multiple driver types utilized in microscopic simulation. Multiple values within the variation range are proportionally assigned to these driver types. The smaller the range of variation in this gap becomes, the lesser the expectation to treat its effects as a variable.

Analysis showed that 15%, 50%, and 85% of drivers in data 1 accepted 0.35, 0.8, and 1.9 s of the leading gaps and 0.6, 1.4, and 3.3 s of the trailing gaps, respectively. The standard deviations of the critical leading and critical trailing gaps were 1.4 and 2.3 s, respectively. Such a range of variation of the leading gap yields about 0.3 s difference per each of ten driver types. Therefore, it was decided to reject treating the leading gap as a variable in this study. Instead, a single critical leading gap value was employed — a single critical gap value has been used in current simulation practice.

4.2. Target-lane density

Data 1 was partitioned into four different categories based on traffic density observed in the target lane: 20, 30, 40 and 50 vehicles per km (veh/km). In each category, the distribution of the lane-changing locations was specified by referencing five different sections of the acceleration lane. These sections were divided into equal parts by 10 rubber cones at sites A and B (Fig. 1). The described data categorization enabled the authors to verify whether traffic density in the target lane affects the lane-changing locations in an acceleration lane. Comparison was made based on the percent distance driven to the length of merging lane. This was because the characteristics and relationships between the distributions of data from sites A and B, utilizing two different merging lengths, were unknown at this stage. Figure 2 depicts the test results.

Fig. 2. Comparison of the distribution of merging locations with different densities on a target lane: (*a*) 20 vehicles/km (veh/km), (*b*) 30 veh/km, (*c*) 40 veh/km, and (*d*) 50 veh/km density on a target lane.



The test results demonstrated that the distributions of the lane-changing locations varied with target-lane density. When

Fig. 3. Comparison of the distribution of critical trailing gaps from sites A and B based on the segments classified by Sturge's method (Yang 1997): critical gaps in segment (*a*) 1, (*b*) 2, (*c*) 3, (*d*) 4, (*e*) 5, (*f*) 6, (*g*) 7, and (*h*) 8.

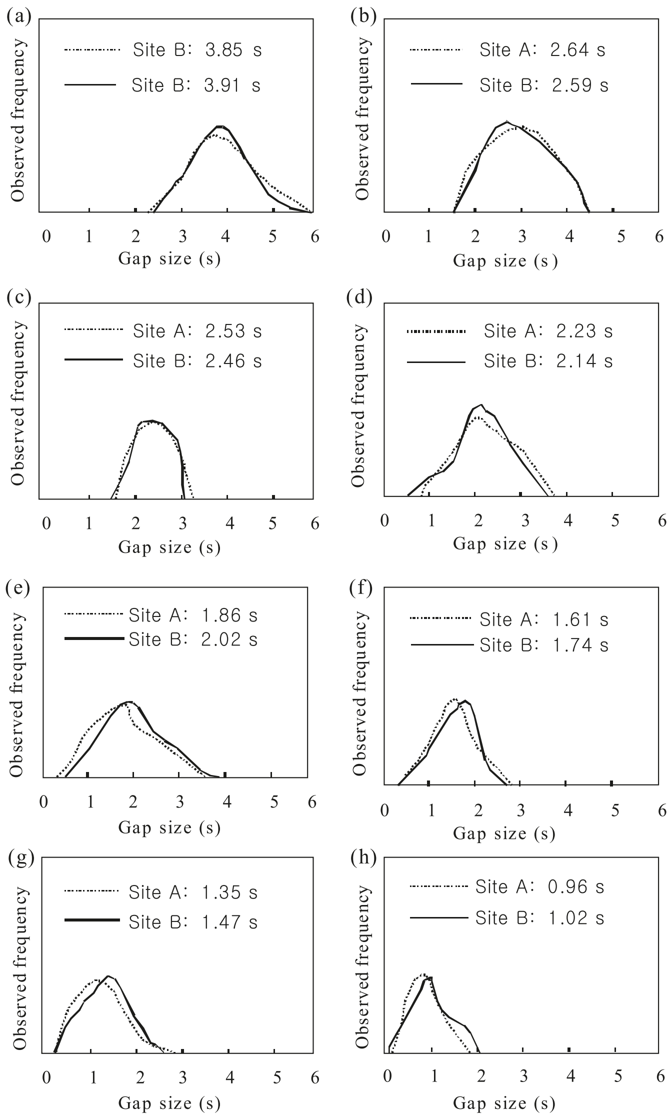


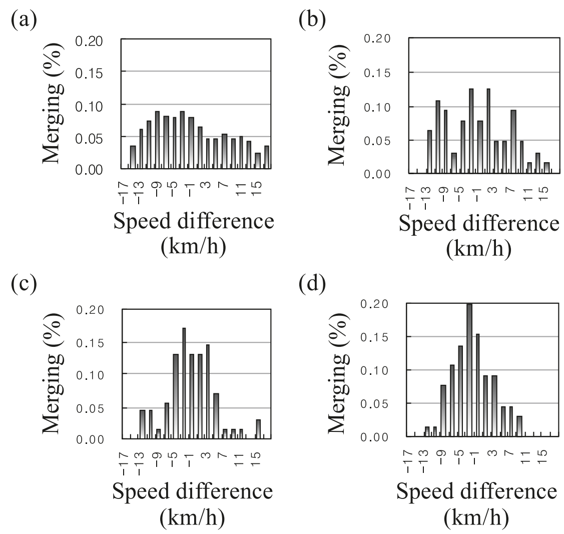
Table 1. Results of goodness-of-fit tests: pairwise comparisons of trailing gap distributions from sites A and B.

Segment ID	Computed value of χ^2	Critical value of χ^{2a}
1	1.52	$\chi^2_{0.05,3} = 7.81$
2	0.56	$\chi^2_{0.05,3} = 7.81$
3	1.51	$\chi^2_{0.05,3} = 7.81$
4	1.44	$\chi^2_{0.05,4} = 11.07$
5	3.85	$\chi^2_{0.05,4} = 11.07$
6	0.61	$\chi^2_{0.05,3} = 7.81$
7	1.82	$\chi^2_{0.05,3} = 7.81$
8	1.15	$\chi^2_{0.05,3} = 7.81$

Note: All results reject null hypothesis that critical gap distributions from pairs of segments from the field sites do not match.

[a] $\chi^2 = \Sigma_i\,[(\text{observed}_i - \text{expected}_i)^2 / \text{expected}_i\,]$, where i is the index of trailing gap data. Subscripts represent the level of significance and degree of freedom, respectively.

Fig. 4. Relative speeds observed on merging segments classified by Sturge's method (Yang 1997): relative speed difference in segments (*a*) 1 and 2, (*b*) 3 and 4, (*c*) 5 and 6, and (*d*) 7 and 8.



the density was low, lane changes occurred closer to the beginning or middle of the acceleration lane (Figs. 2*a* and 2*b*). When density was high, lane changes occurred closer to the end of the acceleration lane (Figs. 2*c* and 2*d*). The results support the results of Wattleworth et al. (1967) and Kita (1993) that drivers tend to accept smaller critical gaps as the remaining length of the acceleration lane decreases.

4.3. Locations on an acceleration lane

Distributions of the critical trailing gaps from sites A and B were grouped separately based on the proportional lengths of the acceleration lanes. A set of comparison tests were run to determine whether the distributions of critical gaps from those sites were proportionally comparable to the lengths of their acceleration lanes. No merging activity occurred in the initial 30 m section, beginning from the nose (Fig. 1). This section was, thus, not considered in the comparisons.

The number of segments of acceleration lanes was statistically determined by Sturge's method (Yang 1997), which is used to determine the optimal number of classes based on sample size. It is given by the following equation:

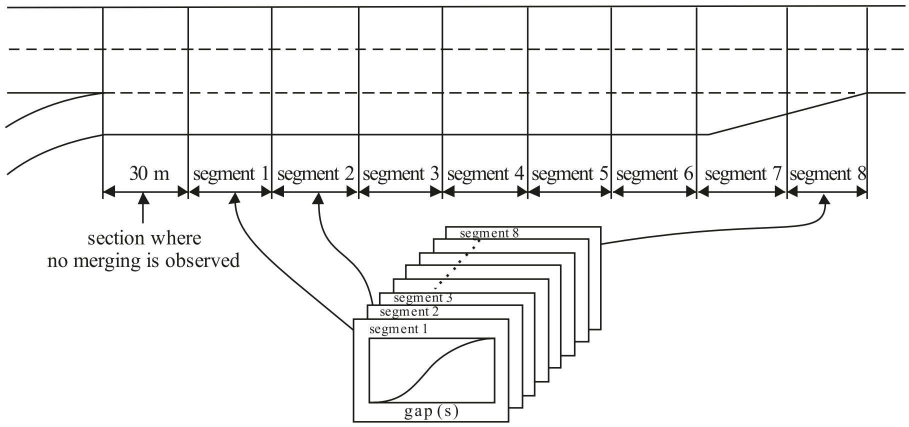
$$[1] \qquad k = 1 + 3.32\,\log n$$

where k is the number of classes (segments) and n is the sample size.

It was found that the ideal number of segments in this case was eight. Distributions of the critical trailing gaps from sites A and B in each segment of the acceleration lanes were compared. Figure 3 illustrates the results. The results showed that the distributions of the trailing gaps from eight different segments in sites A and B were proportionally comparable, segment by segment.

A set of statistical comparison tests, the χ^2 tests, was performed to check pairwise whether these distributions were comparable (at the 95% confidence level). The test results showed that the distributions of critical trailing gaps from the two sites were proportionally comparable, segment by segment, despite different absolute lengths of the accelera-

Fig. 5. Application of the proposed trailing gap acceptance model.



tion lanes (Table 1). The results imply that gap acceptance behavior is influenced not only by the absolute length of the acceleration lane, but also by the fractional distance (from a vehicle's location to the end of the acceleration lane) along the acceleration lane.

4.4. Relative speed

To merge safely, a driver generally needs to adjust his or her speed relative to the trailing vehicle in a target lane. Figure 4 shows the distribution of relative speeds from data 1, depicting the range of the relative speeds accepted for lane changes and changing trends of relative speeds along an acceleration lane.

The relative speed data from data 1 were categorized into four groups (segments 1 and 2, segments 3 and 4, segments 5 and 6, and segments 7 and 8). Figure 4*a* shows that the observed relative speeds are widely distributed, from –15 to +17 km/h, compared with those shown in Fig. 4*d*. Figure 4*d* shows that the kurtosis of the observed distribution is relatively higher in segments 7 and 8. It was concluded that a merging driver tended to accept smaller relative speeds (absolute values) when he or she is closer to the end of the acceleration lane. This supports the finding of Worrall et al. (1967) that merging behavior is affected by relative speed.

Figure 4 shows that the observed relative speeds are mostly within ±15 km/h. In other words, drivers do not accept gaps when the relative speed is outside that range. In addition, it was found from the cumulative distribution of the relative speed data that 85% and 50% of drivers merged within relative speed ranges of ±10.5 and ±5 km/h, respectively.

5. Model development

A gap acceptance model for a merging driver was developed based on the findings from data 1. The proposed gap acceptance model should explain driving behavior that varies with driving situations. These situations should be characterized by several parameters, including the following: target-lane density, sizes of the leading and trailing gaps, relative speed between merging and trailing vehicles, and vehicle location in the acceleration lane.

Table 2. Results of goodness-of-fit tests: pairwise comparisons of trailing gap and normal distributions.

Segment ID	Computed value of χ^2	Critical value of χ^{2a}
1	4.95	$\chi^2_{0.05,3}$ = 7.81
2	3.12	$\chi^2_{0.05,3}$ = 7.81
3	4.07	$\chi^2_{0.05,3}$ = 7.81
4	5.02	$\chi^2_{0.05,4}$ = 11.07
5	9.88	$\chi^2_{0.05,4}$ = 11.07
6	5.52	$\chi^2_{0.05,3}$ = 7.81
7	5.54	$\chi^2_{0.05,3}$ = 7.81
8	4.84	$\chi^2_{0.05,3}$ = 7.81

Note: All results reject null hypothesis that critical gap distributions from each segment do not follow normal distribution.

[a]Refer to footnote *a* of Table 1

5.1. Independent variables

It should be noted that the concept of a critical gap used in the traditional model already accounts for target-lane density. When target-lane density is high, a merging vehicle is less likely to find an acceptable gap and the mean remaining distance to the end of an acceleration lane decreases. Conversely, when target-lane density is low, a merging vehicle is more likely to find an acceptable gap and tends to merge onto the highway earlier in the acceleration lane. The effect of density in a target lane on a driver's merging behavior can be accounted for by adjusting the critical gap size according to the location of a merging vehicle in the acceleration lane.

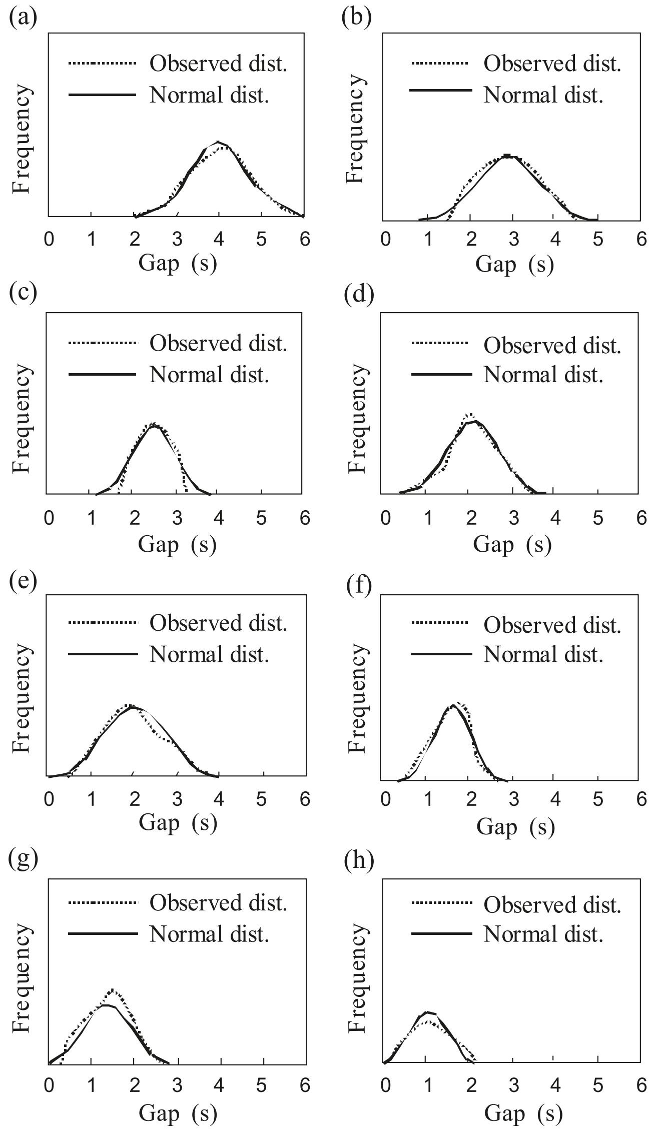
As discussed in the previous sections, the proposed model handles the critical leading gap as a constant and relative speeds were within ±15 km/h in all segments (Fig. 4). Thus, the proposed model uses a constant critical leading gap and a constant critical relative speed.

The proposed model selectively updates the critical trailing gap during the simulation. A typical critical trailing gap distribution was developed for each segment of the acceleration lane. The proposed model selectively adopts a critical value based on the distribution by referencing driver type and the segments of the acceleration lane.

5.2. Incorporation with microscopic simulation

The proposed model should be ready for incorporation into microscopic traffic simulation. The model should reflect

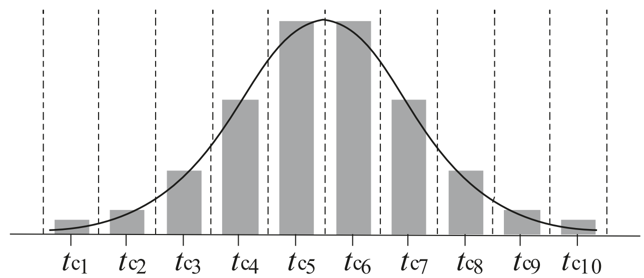
Fig. 6. Comparison between distribution of the trailing gaps observed and normal distributions calibrated from them in segments classified by Sturge's method (Yang 1997): (*a*) segment 1, (*b*) segment 2, (*c*) segment 3, (*d*) segment 4, (*e*) segment 5, (*f*) segment 6, (*g*) segment 7, and (*h*) segment 8. dist., distribution.



the diversity of driving patterns in a population of drivers, and also be highly compatible with the general computational structure of traffic simulation.

The simulation structure of the proposed gap acceptance model was prepared so that it could be readily integrated with existing microscopic simulation techniques. Figure 5 presents the simulation structure of the proposed gap acceptance model. A merging vehicle runs downstream from segment 1 on an acceleration lane. In simulation time, the critical trailing gap assigned to a merging vehicle changes depending on its current segment. The critical gap should be updated by referring to the driver type initially assigned to the vehicle in simulation. Driver types are discussed later in this paper.

Fig. 7. Selection of the critical gaps from a calibrated distribution. t_{ci}, critical gap for driver type *i*.



The structure described in the previous paragraph was used to determine a set of critical trailing gaps. As noted above, the distributions of the accepted trailing gaps from corresponding segments in sites A and B were proportionally and statistically comparable. By combining the results from both sites, a single distribution of the critical trailing gaps was developed for each segment, thus giving eight different distributions (one for each segment of the acceleration lane). Each distribution was then tested to determine whether it matched a given probability distribution function at a 95% confidence level. The χ^2 goodness-of-fit tests confirmed that all distributions were approximately normally distributed (Table 2). Figure 6 compares the distributions of the critical trailing gaps from sites A and B and the (normal) distributions calibrated for them.

Simulation models generally use several types of drivers. The model developed in this paper used 10 different driver types, necessitating the determination of 10 different critical trailing gap sizes. These were determined based on the cumulative distribution function of the calibrated normal distributions illustrated in Fig. 6. Ten different threshold values, each indicating a 10% change of cumulative probability, were used as the critical trailing gaps for these driver types. Figure 7 illustrates the selection procedure of the values for the critical gaps from the calibrated distribution. When the different numbers of driver types are utilized in simulation, the critical values can also be determined for them through the method with different percent changes of cumulative probability.

The structure of the proposed model can easily be realized in microscopic traffic simulation. Equation [2] gives the mathematical expression of the model

$$[2] \qquad \mu_{ij} = \begin{cases} 1 & \text{if } g_{ij} \le g \\ 0 & \text{if } g_{ij} > g \end{cases}$$

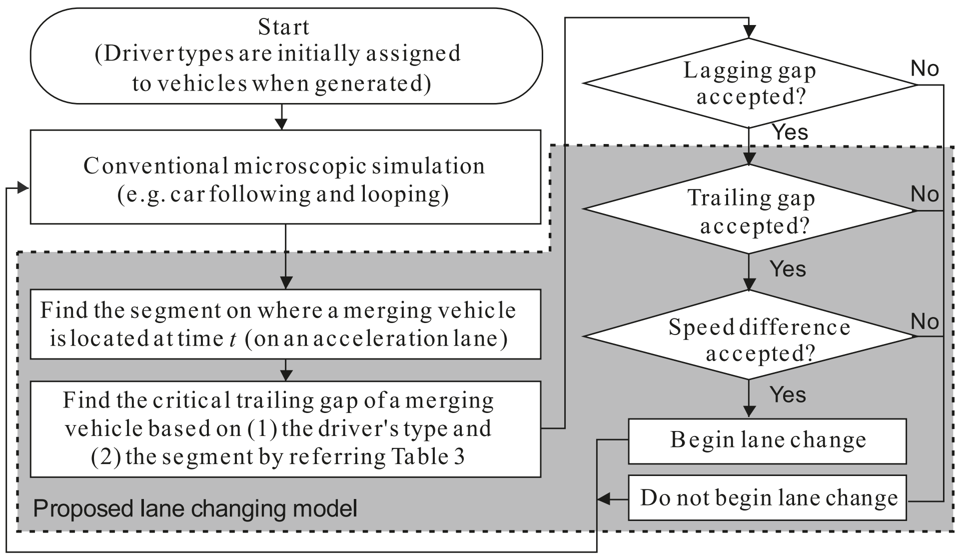
where μ_{ij} is the gap acceptance (= 1) or refusal (= 0), g_{ij} is the critical trailing gap for driver type *i* and section *j* (in s), and *g* is the trailing gap size on the target lane (in s).

Table 3 gives eight sets of 10 different critical gaps extracted from the calibrated distributions shown in Fig. 6. Each set is prepared for the eight segments of the acceleration lane. One trailing gap should be used in simulation, depending on the merging vehicle's current segment and driver type. Figure 8 briefly illustrates the flow chart of the computational procedure of the proposed lane-changing model. The shaded area includes the computational components proposed in this study.

Table 3. Critical groups and critical gap acceptance by acceleration lane segment (unit: s).

	Segment ID							
Index of driver types	1	2	3	4	5	6	7	8
1	6.00	5.30	4.00	3.80	4.00	2.97	2.70	2.05
2	4.80	3.67	3.20	2.85	2.90	2.25	2.06	1.61
3	4.60	3.50	2.80	2.60	2.60	2.00	1.82	1.42
4	4.30	3.25	2.75	2.45	2.42	1.93	1.67	1.31
5	4.20	3.05	2.60	2.30	2.25	1.80	1.53	1.20
6	3.85	2.90	2.50	2.10	2.04	1.68	1.38	1.10
7	3.70	2.65	2.40	1.90	1.85	1.55	1.23	0.95
8	3.60	2.40	2.31	1.80	1.65	1.42	1.10	0.70
9	3.35	2.20	2.10	1.65	1.40	1.25	0.95	0.58
10	3.00	1.90	1.80	1.30	1.10	1.08	0.68	0.42

Fig. 8. Flow chart of the proposed lane-changing procedure.



5.3. Summary of the proposed model

In summary, the proposed lane-changing gap acceptance model for merging considers the critical leading gap, critical relative speed, and critical trailing gap. The model utilizes constant values for the critical leading gap and critical relative speed, and updates the value of the critical trailing gap for a merging vehicle during simulation, depending on the driver type and segments of the acceleration lane.

6. Test of the proposed model

A microscopic traffic simulation model, named "Merging Simulation" (MS), was coded by the authors in the Visual Basic programming language to test the proposed model. The proposed lane-changing gap acceptance model was implemented in MS. This model checks the location of the vehicle, the trailing and the leading gaps on a target lane, and the relative speed between merging and trailing vehicles, and updates the critical trailing gap of a merging vehicle.

The MS model simulates traffic flow with 1 s time steps. It randomly assigns vehicle driver types in accordance with a normal distribution, and employs two nonlinear car-following models (Gerlough and Huber 1975). These first and second models are the ones raising the denominator of a coefficient (the measure of the sensitivity) in the generalized car-following equation, to the first and the second power, respectively. The numerators of these first and second models are equivalent to the velocity at optimum flow and the free-flow speed, respectively. Detailed information on these models can be found in general traffic-flow-theory literature. The MS model selectively adopts one of these car-following models during simulation, as suggested in previous research (Kim 2000), using the first model when the vehicle's speed is at least 90 km/h for the second model.

The MS simulation results were compared against data 2, the field data reserved for model validation, to evaluate the performance of the proposed gap acceptance model. Three indices were employed for the comparisons. The first was the distribution of the merging locations with respect to the traffic density on a target lane. The second was the cumulative difference between relative speeds if merging and trail-

Fig. 9. Comparison between the "Merging Simulation" results and the field database on lane-changing locations (as affected by target lane density): percent vehicles merging when density of main stream is (*a*) 20 vehicles/km (veh/km), (*b*) 30 veh/km, (*c*) 40 veh/km, and (*d*) 50 veh/km.

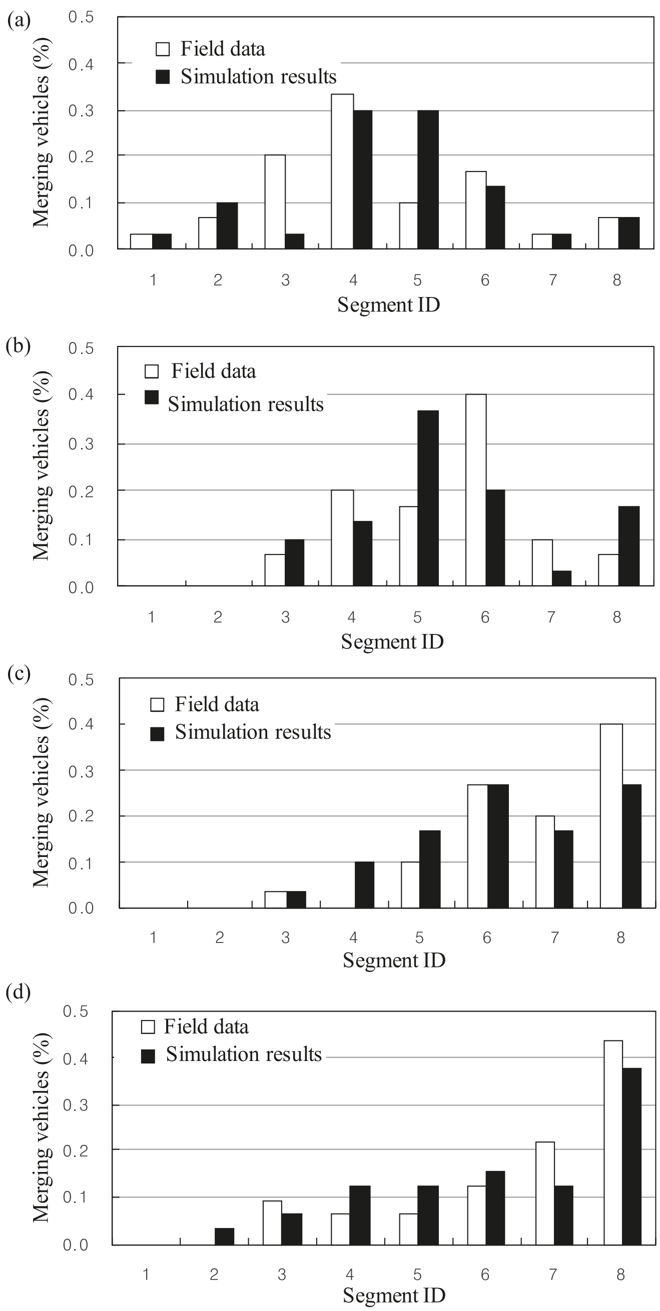


Table 4. Results of the paired *t*-tests (distributions of merging locations from simulation versus field observations).

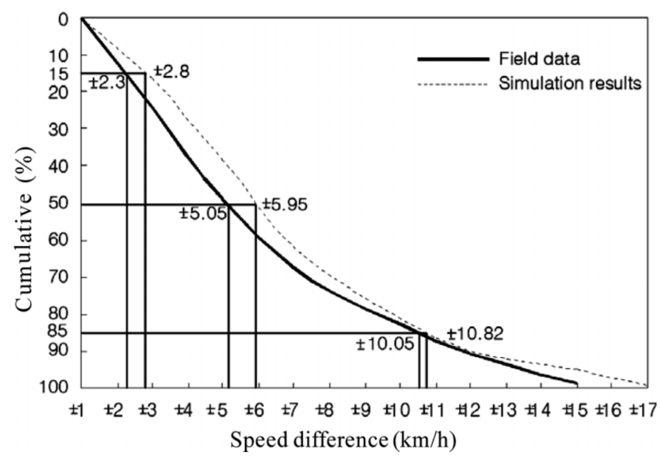
Density on main line[a] (veh/km)	Computed value	Critical value[b]
Site A		
20	–1.83	$t_{14,0.025} = 2.145$
30	–1.70	$t_{14,0.025} = 2.145$
40	1.16	$t_{14,0.025} = 2.145$
50	1.41	$t_{14,0.025} = 2.145$
Site B		
20	–1.60	$t_{14,0.025} = 2.145$
30	1.28	$t_{14,0.025} = 2.145$
40	1.59	$t_{14,0.025} = 2.145$
50	1.72	$t_{14,0.025} = 2.145$

Note: All results reject null hypothesis as simulated distributions of merging locations affected by the density of main line flow differ from the ones observed in the field.

[a]Density on an edge-side lane adjacent to an acceleration lane. veh, vehicles.

[b]$t_{14,0.025}$, *t*-statistic value when degree of freedom is 14 and level of significance is 0.05 (two-tailed test).

Fig. 10. Comparison of the relative speed between "Merging Simulation" results and field data.



ing vehicles at the time of merging. The third is the distribution of trailing gaps accepted for merging.

6.1. Merging locations affected by density on a target lane

The MS simulation results and data 2 were compared, with particular reference to the relationship between merging locations and target lane density. Figure 9 illustrates the results; it shows that the simulation results closely match field data. The merging location becomes closer to the beginning of the acceleration lane when target lane density is low, and closer to the end when density is high. Paired *t*-tests were carried out at the 95% confidence level to determine whether the MS simulation statistically explained the field data. The results gave strong statistical evidence that the simulation results and field data were significantly comparable (Table 4).

6.2. Relative speed at the time of merging

Figure 10 shows a comparison of the field data and the MS simulation results with respect to the relative speeds between merging and trailing vehicles. The results showed that the MS simulation results closely matched the field data. The cumulative 85% of relative speeds from the simulation results and data 2 were ±10.05 and ±10.82 km/h, respectively. A goodness-of-fit test (a χ^2 test) was carried out at the 95% confidence level to determine whether the related speeds from the MS simulation and data 2 were statistically

Table 5. Statistical comparison results: distributions of relative speeds from simulation versus field observations.

Computed value of χ^2	Critical value of χ^{2a}	Results
11.07	$\chi^2_{0.05,211} = 245.88$	Reject null hypothesis[b]

[a]Refer to footnote *a* of Table 1.

[b]Null hypothesis, simulated distributions of speed differences at merging differ from the ones observed in the field.

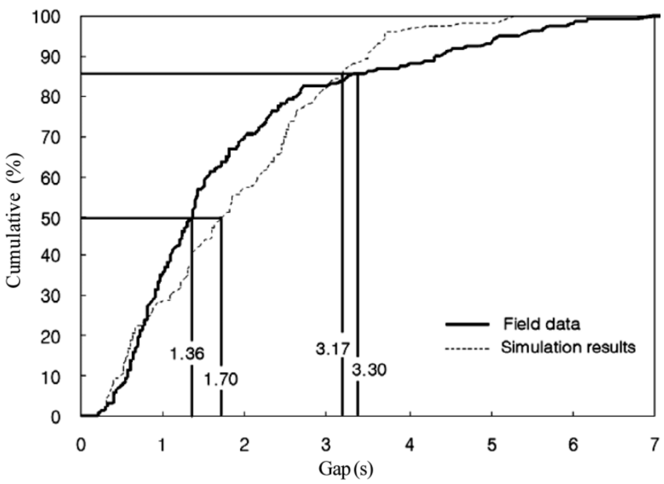
Table 6. Statistical comparison results: distributions of trailing gaps from simulation versus field observations.

Computed value of χ^2	Critical value of χ^{2a}	Results
14.47	$\chi^2_{0.05,312} = 345.19$	Reject null hypothesis[b]

[a]Refer to footnote *a* of Table 1.

[b]Null hypothesis, simulated distributions of critical trailing gaps differ from the ones observed in the field.

Fig. 11. Comparison of trailing gap speeds between "Merging Simulation" results and field data.



comparable. The results gave strong statistical evidence that the simulation results and field data were significantly comparable (Table 5).

6.3. Cumulative distribution of trailing gaps

Figure 11 shows a comparison between the MS simulation results and data 2 with respect to the cumulative distribution of the trailing gaps. The figure shows that the MS simulation results agree well with the field data. The cumulative 85% of the trailing gaps of merging vehicles in the MS simulation and data 2 were 3.30 and 3.17 s, respectively. The cumulative 50% of the trailing gaps from the MS simulation and data 2 were 1.36 and 1.70 s, respectively. A goodness-of-fit test (a χ^2 test) was performed at the 95% confidence level to determine whether the simulation results were comparable to the field data. The results gave strong statistical evidence that the simulation results and field data were significantly comparable (Table 6).

7. Conclusions and recommendations

A gap acceptance model for merging in microscopic traffic simulation was proposed in this study. The proposed model, a condition model for mandatory lane change, simultaneously considers three different conditions: when the trailing gap is larger than the critical one, when the leading gap is larger than the critical one, and when the relative speed is within the acceptable range. The model was designed to reflect the variety of driving patterns and to be easily integrated into the general computational structure of traffic simulation.

It was found from the field data that the merging locations depended on traffic density in the target lane. The critical trailing gaps from the segments at sites A and B were (pairwise) proportionally comparable in each corresponding segment, despite the different lengths of the acceleration lanes. It was statistically ascertained that eight different distributions (combining the data from sites A and B) were normal. Critical gaps for multiple driver types were determined based on the cumulative distribution functions of the calibrated normal distributions. The proposed model employs a set of the critical trailing gaps dependent on driver type and current segment of the acceleration lane. The model can be easily incorporated into microscopic simulation.

Tests compared data 2 and the results of the simulation utilizing the proposed model with respect to three performance indices: merging locations with respect to traffic density on a target lane, relative speeds at the time of merging, and cumulative leading gaps between merging and leading vehicles. It was statistically ascertained that simulation results were significantly comparable to the field data.

It was interesting to find that the critical trailing gaps observed in this study in Korea are significantly similar to those measured in the UK. Sultan et al. (2002) reported that the mean values of the trailing gaps accepted in UK cut-in lane changes varied from 0.42 to 0.59 s, depending on the cut-in situations. Cut-in lane changes are, practically, the mandatory lane changes in extreme situations. Such aggressive lane changes are easily observed near the end of an acceleration lane. The values suggested in the UK are very close to the ones assigned to driver types 9 and 10 on segment 8 (the last segment) in this study, 0.42 and 0.58 s, respectively. It should be noted that data 1 contains the mandatory lane changes and that the cumulative 10%–20% of drivers on the aggressive side use those levels of critical trailing gaps.

When using the proposed model in countries with driving cultures and laws that are significantly different from those in the UK and Korea, it may be necessary to recalibrate the critical trailing gaps based on the driving characteristics of local drivers. Different critical gap distributions can be expected in different driving environments.

The results of this study are limited to urban freeway merging. The length of an acceleration lane in rural freeways is usually much longer than those of urban freeways. Due to the difficulty of recording a whole length of a long acceleration lane, driving behavior on rural freeways was excluded from the study.

Limitations of this study also include the number of freeway merging areas considered. An increase in the number of sample sites is desirable. There are, however, some practical constraints in increasing the number of the sites. These include safety issues in placement, difficulty in situating data collection equipment, and an increase in processing time. Data reduction is difficult without time consuming procedures.

It would be reasonable to start with the findings from two different sites capturing drivers' merging behavior as affected by the respective simulation situations. Further research based on field data from more field sites is recommended for reinforcing the findings from this study.

It is necessary to test the performance of the proposed model with commercial simulation software and to compare it to existing models. It is difficult to embed the proposed model into commercial software because of unreleased source code. However, some commercial software includes application programming interface (API) functions that enable users to intervene in the simulation. Testing of the proposed model with commercial simulation software by utilizing its API functions requires further study.

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