Development of A New Merge Capacity Model and the Effects of Ramp Flow on the Merge Capacity

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Abstract
Freeway merge areas are recognized as the most common segment of recurrent freeway congestion as two separate traffic streams join to merge a single stream. Over the years, several studies have attempted to explain and analyze a merge capacity phenomenon, however relatively few analytical techniques have been developed to evaluate the traffic flow in these areas. This study described a new interpretation of merge capacity. The gap acceptance theory was used for the development of merge capacity model and Erlang distribution was selected for the definition of time headway distributions. This study has developed a generalized model that could reflect the merge capacity based on shoulder lane volume and the critical gap. Results show that the merge capacity decreases as the ramp volume and the critical gap increase and the shoulder lane volume decreases. The value of merge capacity could vary in some degree due to the sizes of these variables. Therefore, there need to introduce the new definition of merge capacity and to consider some variables like the ramp volume and the critical gap which affect the merge capacity.
1. INTRODUCTION

Freeways are originally conceived and designed to provide continuous, free-flow, high-speed movement of traffic on limited-access facilities. Freeways are generally perceived as the highest level of road facility with full control of access and two or more lanes for the exclusive use of traffic in each direction. These are only type of highway facility that provides completely “uninterrupted” flow. Although they are originally designed for uninterrupted flow, several locations on freeway system become congested with the continuous increase of traffic demand.

Among these locations, merge areas are recognized as the most common segment of recurrent freeway congestion as two separate traffic streams join to merge a single stream. The interference of merging movements in traffic stream affects the traffic characteristics of freeway and ramp around the merge area. As noted in US Highway Capacity Manual (HCM) of 2000, this influence area extends to a distance of 450 meters including acceleration lane at the downstream of an on-ramp (1). Such turbulence in traffic flow including speed variability and lane changes may result in breakdowns and congestion.

Over the years, several studies have attempted to explain and analyze traffic characteristics and operations at merge areas, however relatively few analytical techniques have been developed to evaluate the traffic flow in such areas. One of the widely used approaches is US HCM, which is an empirical method developed using field observations. This methodology has three major steps: [1] determination of the flow entering lanes 1 and 2 immediately upstream of the merge influence area, [2] determination of the capacity value and comparison with existing demand flows, and [3] determination of the density within the ramp influence area and the level of service based on this variable. It does not take any direct relationship between a ramp and a freeway mainline flows into consideration, though this relationship strongly affects the merge capacity within these areas. Furthermore, the capacity values for merge areas assume to have fixed values, where only free-flow speed and the number of lanes in one direction are taken into account disregarding any influences of ramp flow.

Another approach is the gap acceptance theory, which was based on the mathematical and theoretical method that had mainly been studied during the 1960s. In comparison to HCM methodology, the gap acceptance model can be constructed on the relationships between the ramp and the shoulder lane flows that can reflect the influences caused by the ramp flow. It also makes it possible to take the critical gap for road conditions and the headway distribution for traffic conditions into account. However, due to the complexity of the model and difficulties in validation, the gap acceptance model has not been widely used despite its strong reflection of ramp flow and characteristics.

In the 1960s, Drew et al. developed theoretical models and parameters for freeway merging process and established a statistical relationship between the percent gap acceptance and gap size (2). This relationship was applied to single and multiple entry merge areas. Drew et al., then, presented a new approach to determine merging capacity using gap acceptance behavior of the drivers and applied this approach to freeway design and control such as ramp metering systems. The influence of on-ramp design characteristics, such as the acceleration lane length, convergence angle and the shape of acceleration lane, were also taken into consideration and were applied to freeway control as the gap acceptance mode of ramp metering. However, this methodology made use of a single Erlang parameter (K=1) for the negative exponential distribution that represented the random arrivals of low volume range. In addition, the authors did not make any attempt to explain the influences of ramp flow on the merge capacity (3).

Recently, some researchers proposed that at ramp merge junctions, breakdown might occur at flows lower than the maximum observed, or capacity flows. Furthermore, it was observed that at the same site and for the same ramp and freeway flows, breakdown might or might not occur. After visual examination of traffic operations at sites where breakdown occurred, they observed that immediately before breakdown, large ramp-vehicle clusters entered the freeway stream and disrupted traffic operations. It was concluded that breakdown was a probabilistic rather than deterministic event and was a function of ramp-vehicle cluster occurrence. Subsequently, a probabilistic model for describing the process of breakdown at ramp-freeway junctions was examined. The model gave the probability that breakdown would occur at given ramp and freeway flows and was based on ramp-vehicle cluster occurrence (4).

In addition, the need for enhancing capacity definition in a way that it embedded the probabilistic nature of the freeway breakdown process was proposed by Lorenz and Elefteriadou. They addressed the need for an enhanced freeway capacity definition that incorporated the probabilistic nature of the freeway breakdown process. The freeway breakdown process was examined in detail for over 40 congestion events occurring during the course of nearly 20 days. They developed preliminary models for each site describing the probability of breakdown versus observed flow rate and examined the implications that this probabilistic approach to breakdown had on the current definition of freeway capacity. A revised, probabilistic freeway capacity definition was proposed for use in future editions of the "Highway Capacity Manual" (5).

The objective of this study is to develop a merge capacity model using gap acceptance and several variables that have an influence on the capacity defined by analytical interpretation. To achieve this objective,
this study includes three major steps; definition of volume ranges based on Erlang parameter, derivation of ramp capacity equations for each Erlang parameter, and development of a generalized merge capacity model. These steps, the reflections of proposed model on merge capacity, and shoulder lane and ramp flow relationships are described in detail in the following sections.

2. FORMULATION OF RAMP CAPACITY EQUATION

The capacity at the merge area is based on the interaction between the gap acceptance behavior of entrance ramp drivers and the availability of gaps on the freeway shoulder lane. Merge capacity is a maximum service volume that determines how much entering ramp flow can be accepted to the shoulder lane flow of freeway mainline. Variations in merge capacity are caused by traffic disturbances due to lane changing, acceleration and/or deceleration behaviors. The proposed model procedure is based upon the determination of critical gap and the definition of ramp capacity. The determination of critical gap reflects the geometric conditions and the mechanical capability of ramp vehicles. The variables defining ramp capacity are the shoulder lane volume, the headway distribution and the critical gap.

2.1 Headway Distribution on the Shoulder Lane

In general, time headway distribution and its shape varies for different volume states because of the increasing headway interaction within traffic flow. For example, at low traffic flow levels, there are few headway interactions between vehicles, so that the time headways are somewhat random. As the traffic flow level increases, the headway interactions between vehicles also increase. When the traffic flow level approaches to capacity, vehicles are in car following state.

The Pearson type III distribution is a generalized mathematical model approach to define such phenomenon. That is actually a family of distribution models consist of simpler distribution models. This model becomes a simple Erlang distribution when the shift parameter, \( a \), takes zero value and shape parameter, \( K \), takes on any positive integer value. The \( K \) value can take any integer value from 0 to \( \infty \). If \( K \) is selected to be 1, the form of the resulting distribution is a negative exponential (random) distribution. As the \( K \) value approaches to infinity, the resulting distribution becomes a constant distribution (6).

Following the assumption that the Erlang distribution represents the time headway, the selection of shape parameter \( K \) gains an ultimate importance. \( K \) is affected by road alignments, grade, and other environmental factors; however, the most influential factor is the volume level. Therefore, this study attempts to define the relationship between the shoulder lane volume and \( K \) in model that can calculate \( K \) based on the volume level.

2.2 Volume Range Based on Erlang Parameter (K)

In this study, the mean and the deviation of time headway distribution of the shoulder lane flow is used to define Erlang parameter (K). According to reference (6), this relationship can be defined as follows:

\[
K = \frac{\bar{t}}{s}
\]

where,

- \( K \) = Erlang parameter
- \( \bar{t} \) = the mean time headway (sec)
- \( s \) = the standard deviation of the measured time headway distribution (sec)

In case of the time headway distributions that have the same mean time headway but the different standard deviation of headway, \( K \) takes different values each other: the greater the standard deviation, the smaller the \( K \) is. This simply means that the interrelation within traffic flow is getting weaker.

This study used field observation values to simplify the definition of \( K \) by adjusting it for the various ranges of volumes. Data sets were collected at KwangJu and HoBub interchanges of JungBu expressway in Korea through the video image analysis system. These sites are composed of two lanes of mainline and one lane of ramp. The shoulder lanes in these sites were used for observing time headway of individual vehicles, and \( K \) for each observation was calculated using Equation (1). Taking the shoulder lane volume as an independent variable, the regression analysis was performed to define Erlang parameter (K). The relationship between Erlang parameter (K) and the shoulder lane volume (q) is shown in Figure 1 and the regression statistics results are presented in Table 1.
As a result of the statistical analysis, an $R^2$ value of 0.71 and significant results from a fitness test are obtained. Using the significant coefficient of the regression analysis, the model calculating Erlang parameter ($K$) becomes:

$$K = 0.51e^{2.99q}$$  \hspace{1cm} (2)

where,

$q$ = the shoulder lane volume (veh/sec)

Based on the relationship between $K$ and the shoulder lane volume as defined in Equation (2), the volume ranges to each Erlang parameter ($K$) can be calculated. Now that Erlang parameter ($K$) must be a positive integer according to the definition of Erlang distribution, the calculated $K$ values are rounded to the nearest integer, and the volume ranges to each Erlang parameter ($K$) is shown in Table 2.

In this study, Erlang parameter ($K$) do not have to be greater than 3. If $K$ is greater than 3, the calculated volume value will exceed 2,300 pcp/h which is in general perceived as the maximum lane capacity value on freeway. It is also known that the volume of shoulder lane is usually lower than those of other lanes, because most vehicles change lanes in advance to avoid the conflict with the ramp flow entering freeway. Therefore, $K$=1, 2, and 3 can represent all possible volume ranges of the shoulder lane. Table 2 shows the calculated volume ranges using Equation (2) for $K$=1, 2, and 3. For instance, the shoulder lane volume of 1,306 vph in Table 2 is calculated as Erlang parameter ($K$) is up to 1.5.

### 2.3 Derivation of Ramp Capacity Equations

Consider a single, inexhaustible queue waiting to enter a shoulder lane of traffic stream where $T$ is the critical gap for a ramp vehicle to enter the shoulder lane of freeway mainline and $H$ is another critical gap which is a gap for entry of additional vehicles that consecutively follow the first merging vehicle as shown in Figure 2.

Based on the time headway and the critical gap, the possibility of ramp vehicles to enter the shoulder lane is as follows:

- If the passing time headway, $t$, is less than the critical gap, $T$, no ramp vehicle enters.
- If $t$ is between $T$ and $T+H$, only one vehicle enters.
- If $t$ is between $T+H$ and $T+2H$, two vehicles enter, etc.

Hence, the possible ramp volume entering the shoulder lane per unit time becomes:

$$q_r = q \sum_{i=0}^{\infty} (i+1) \cdot P[T + iH \leq t < T + (i+1)H]$$  \hspace{1cm} (3)

where,

$q_r$ = the maximum ramp volume (veh/sec)

$q$ = the shoulder lane volume (veh/sec)

$T$ = Critical Gap (sec)

$H$ = Another critical gap for entry of additional vehicles (sec)

$P[T + iH \leq t < T + (i+1)H] = \text{the probability of the time headway (t) taking a value between } T + iH \text{ and } T + (i+1)H$

Considering that the negative exponential distribution for $K$=1 represents the distribution of headways in the shoulder lane, the probability density function, $f(t)$, and the cumulative distribution function, $P(h \leq t)$, can be expressed as follows.

$$f(t) = qe^{-qt}$$  \hspace{1cm} (4)

$$P(h \leq t) = 1 - e^{-qt}$$  \hspace{1cm} (5)

Merging the Equation (3), the probability density function and the cumulative distribution function, the maximum ramp volume entering the shoulder lane per unit time for $K$=1 becomes:
\[ q_r = q[e^{-qT} - e^{-q(T+H)}] + 2q[e^{-q(T+H)} - e^{-q(T+2H)}] + \ldots \\
= qe^{-qT} + qe^{-q(T+H)} + qe^{-q(T+2H)} + \ldots \\
= qe^{-qT} \left( 1 + e^{-qH} + e^{-2qH} + \ldots \right) \\
= \frac{qe^{-qT}}{1-e^{-qH}} \quad (6) \]

For \( K=2 \), the probability density function, \( f(t) \), and the cumulative distribution function, \( P(h \leq t) \), are:

\[ f(t) = 4q^2te^{-2qt} \]

\[ P(h \leq t) = 1 - e^{-2qt}[1 + 2qt] \quad (7) \]

In same manners, the maximum ramp volume entering the shoulder lane per unit time for \( K=2 \) becomes:

\[ q_r = q[e^{-2qt}(1 + 2qT) - e^{-q(T+H)}[1 + 2q(T + H)] + 2q[e^{-q(T+2H)}[1 + 2q(T + 3H)] + \ldots] \\
= qe^{-2qt} + e^{2qt(T+H)}[1 + 2q(T + H)] + qe^{-2qt(T+2H)}[1 + 2q(T + H)] + \ldots \\
= q[e^{-2qt} + e^{2qt(T+H)} + e^{2qt(T+2H)} + \ldots] + 2qT[e^{-2qt} + e^{2qt(T+H)} + e^{2qt(T+2H)} + \ldots] \\
+ 2qH[e^{-q(T+H)} + e^{-2q(T+H)} + e^{-2q(T+2H)} + \ldots] \\
= qe^{-2qt} \left[ \frac{1}{1-e^{-2qH}} + \frac{2qT}{1-e^{-2qH}} + \frac{2qHe^{-qH}}{(1-e^{-2qH})^2} \right] \\
= \frac{qe^{-2qt}}{(1-e^{-2qH})^2} \left[ 1 + 2qT + \frac{2qHe^{-qH}}{(1-e^{-2qH})^2} \right] \quad (8) \]

Finally, for \( K=3 \), the probability density function, \( f(t) \), and the cumulative distribution function, \( P(h \leq t) \), are:

\[ f(t) = \frac{27q^3e^{-3qt}}{2} \]

\[ P(h \leq t) = 1 - e^{-3qt}[1 + 3qt + (\frac{3qt}{2})^2] \quad (9) \]

and if this cumulative distribution function merges Equation (3) as the same process like Equations (6) and (8), the maximum ramp volume entering the shoulder lane per unit time for \( K=3 \) becomes:

\[ q_r = \frac{qe^{3qt}}{[1-e^{-3qH}]^2} \left[ 1 + 3qT + \frac{3qH(1+6qT)e^{-3qH}}{(1-e^{-3qH})^2} + \frac{9q^2H^2(1+e^{-3qH})e^{-3qH}}{(1-e^{-3qH})^2} \right] \]

\[ = \frac{qe^{3qt}}{[1-e^{-3qH}]^2} \quad (10) \]

Equations (6), (8), and (10) define the ramp capacities \( q_r \) for different shoulder lane volume ranges \( q \) based on Erlang parameter \( K \) values. For calculating the ramp capacities, it should be defined that another critical gap \( H \) for additional vehicles to merge into a provided gap. For convenience, this study supposed this gap \( H \) was the same as the critical gap \( T \) in case of the ideal and safe merge. Figure 3 shows the relationships between the maximum ramp volume \( q_r \) and the shoulder lane volume \( q \) to each critical gap \( T \). In this figure it is shown that the maximum ramp volume decreases as the shoulder lane volume increases under the same critical gap.

Finally, merge capacity can be calculated as the ramp capacity and the shoulder lane volume are summed each other. Next sections describe to develop a generalized merge capacity model using three ramp capacity equations above and also address the effect of ramp flow on the merge capacity.
3. A GENERALIZED MERGE CAPACITY MODEL

As explained in the previous section, the ramp capacity is expressed by three different equations for different shoulder lane volume ranges. Using these equations for capacity calculation is too complex to be a convenient tool for practical applications. Therefore, a generalized model, which includes a definition for all volume ranges at an appropriate level of precision, is needed. To accomplish this objective, the first step is to decide which variables should be used in the model to reasonably represent the merging phenomenon.

3.1 Selection of Independent Variables

According to equations formulated above, the maximum ramp volume directly relates to shoulder lane volume, and this means that one variable can automatically be defined if another variable is decided. To understand the relationship between the components of merge capacity definition, the relationship between the shoulder lane volume and the maximum ramp volume is analyzed under the various critical gap values. As shown in Figure 3, the maximum ramp volume decreases as the shoulder lane volume increases for each critical gap value. For smaller critical gap values, the shapes of lines look like almost linear. As the critical gap value increases, the relationships become more asymptotic and less sensitive to the high levels of shoulder lane volume. Figure 3 simply shows such a tendency as mentioned above. For instance, in Figure 3, only ramp volume of 10 vehicles can merge into the shoulder lane for an hour in case the shoulder lane volume is 1,900 veh/hr and the critical gap (T) is 7 second. This simply means that the probability for ramp vehicles to enter the shoulder lane under these conditions is very low and then it is very hard for the ramp vehicles to merge in this circumstance. According to the result of Table 2, Figure 3 is divided in 3 regimes and each regime coincides with the boundary of shoulder lane volume determining by each Erlang parameter.

Figure 4 illustrates the relationship between the merge capacity and the ramp volume for K = 2. According to the Figure 4, the merge capacity becomes smaller as the ramp volume increases; the higher the ramp volume, the lower the merge capacity is. Furthermore, as the critical gap value increases, the merge capacity decreases very rapidly. For instance, the merge capacity shows a rapid decrease in response to a very small change in the ramp volume for T = 7. However, the merge capacity decrease for T = 2 is more gradual compared with that of T = 7.

Merge of ramp vehicles to the shoulder lane flow causes the lane and speed changes of flow in shoulder lane to avoid the conflict with the ramp flow. Such reactions may cause disturbance in mainline stream. Considering the effect of merging vehicles on the mainline stream, the sizes of the ramp volume and the critical gap at a merge area are the most influential factors for defining the merge capacity.

Based on the relationships described above, the critical gap and the ramp volume must be selected as model variables for developing a merge capacity model. However, it is known that it is easier to obtain the shoulder lane volume measurements compared to the ramp volume because there are no vehicle detectors installed on ramp in Korea. Because the shoulder lane volume is a variable directly related to the ramp volume, in this study the shoulder lane volume was used as an independent variable instead of the ramp volume to form a merge capacity model. Taking the critical gap (which represents geometric conditions at a merge area) and the shoulder lane volume as independent variables, a regression analysis has been performed for each critical gap from T = 2 through 7.

3.2 Development of A Generalized Merge Capacity Model

According to the results of the regression analysis, linear and exponential models presented the best fit to the merging equations derived in the previous section; high R² values are calculated: 0.91 for the linear function and 0.89 for the exponential function. Figure 5 shows the results of the regression analysis for two extreme critical gap values 2 and 7. To verify the regression curves, this study tried to collect the traffic data in the field, but it was not possible to collect the various conditions of flow rate. The data for the performance of this curve must be composed of the various data set that have the high volume of shoulder lane and the low ramp volume at each site and vice versa. However, it is not easy to obtain such a data in the real field. That is because when the ramp volume is high, the shoulder lane volume is also high in a real world situation.

As the shape of the models are compared with results calculated by using three merging Equations (6), (8), and (10), the linear model shows a better fit at low volume levels for T = 2 and a better fit at high volume levels for T = 7. In the real traffic conditions, it is more likely to observe high volume levels if the mean time headway is low and low volume levels if the mean time headway is high. Therefore, the linear model is selected for the generalized merge capacity model. The properties of statistical analysis for the linear model are shown in Table 3.
Using the parameters from the statistical results of regression analysis and the t-test, the generalized merge capacity model can be proposed as follows:

\[ C_M = 0.621559V_S - 188.2387T + 1757.058 \]  
\[ (11) \]

where,

- \( C_M \) = Merge Capacity (pc/hr/ln)
- \( V_S \) = Shoulder Lane Volume (pc/hr/ln)
- \( T \) = Critical Gap (sec)

The generalized model shows that the merge capacity value increases as the critical gap decreases and the shoulder lane volume increases. Similarly, as the critical gap increases and the shoulder lane volume decreases, the merge capacity is on the decrease. It means that the merge capacity could vary according to the sizes of the shoulder lane volume and the critical gap.

This study developed a regression model to determine the critical gap that was needed for the generalized merge capacity model and that was one of the most important variables in describing the merging process. This model used the data that was collected from 3 merging sites with two-lane freeway (one direction) and one lane on-ramp. The collected data items were the speeds of individual ramp vehicle along the acceleration lanes, the locations of the merging points, the vehicle counts, and the accepted gaps. By applying regression analysis to the data, an equation for the critical gap was produced.

\[ \text{Critical Gap (T, sec)} = 4.9088 - 0.005678D - 0.000075868Sr^2 \]  
\[ (12) \]

Where,

- \( D \) is the distance from nose to merging point on the acceleration lane
- \( Sr \) is the speed of ramp vehicle

The value of \( R^2 \) is 0.71 for the critical gap equation and the result of t-test is significant in terms of the parameters used for the regression model. The acceleration lane length at merge areas can be substituted for the distance (D) in Equation (12) as it means the length that the ramp vehicles need to accelerate to merge into the mainline flow.

In general heavy vehicles cannot accelerate as well as passenger vehicles on the acceleration lane and such a slow moving merging may need the greater critical gap and the merge capacity becomes smaller value compared to a fast moving merging. The critical gap needed for various merging speed can be defined by Equation (12). Therefore, the merge capacity model developed can recognize such various merging types by the speed of merging.

In practice, the merging may become forced one as the shoulder lane volume increases above a certain level and the accepted gap may become smaller than the critical gap needed by ramp vehicles. This model can consider this phenomenon as the critical gap is dynamically applied to accommodate various merging situations.

As the model was directly derived from the shoulder lane volume and the critical gap, the model could be applied to more than two-lane freeways in some degree. The shoulder lane volume for the model is a general value regardless of the occurrence of lane changing before the merging area on multi lane freeways. Certainly, the effect of lane changes from the shoulder lane to left lanes is not considered, and that is not the scope of this study.

Being different from the results of existing studies, it is shown that the merge capacity is not a fixed value but varied values. Figure 6 illustrates the relationship between merge capacity and other two variables like the critical gap and the shoulder lane volume. In Figure 6 the shoulder lane volume needs to have some boundary conditions by critical gap sizes because the critical gap is a function of mean time headways i.e. rate of flow. For the critical gap of 2 second, the developed model will be useful in case the shoulder lane volume is in average smaller than 1,800 pcp/h/l and in sequence 900 pcp/h/l for the critical gap of 4 second and 600 pcp/h/l for the critical gap of 6 second.

4. CONCLUSIONS

Over the years, several studies have attempted to explain and analyze the characteristics and phenomena of merge capacity, however relatively few analytical techniques have been developed to evaluate the traffic flow at merge areas, especially the merge capacity. For instance, in US HCM, the merge capacity was considered as a fixed value under same free-flow speed and the number of lanes without considering the influence of the ramp flow. In addition, Drew et al. presented a new approach to determine the merge capacity using gap acceptance behavior of the drivers and employed this approach to freeway design and control like ramp metering systems. However, this methodology considered only an Erlang parameter (K=1) to cover low volume range and did not describe the effect of ramp flow on the merge capacity. Recently, the need for enhancing capacity definition in a
way that it embodies the probabilistic nature of the freeway breakdown process was proposed by Lorenz and Elefteriadou. They proposed that the capacity could vary in some degree due to the probabilistic nature.

To find out the variation of capacity, this research attempted a mathematical approach rather than empirical approach due to the difficulties of data collection that could reflect the various combinations of ramp and shoulder lane flows, and also decided the variables that have the effect on the merge capacity. Thus, this study presented a new approach for the merge capacity characteristics representing the probabilistic nature of the merging phenomenon and described the affects of variables such as the critical gap, the ramp volume, and the shoulder lane volume on the merge capacity.

The ranges of shoulder lane volume were defined for each Erlang parameter and the ramp capacity equations were derived for each Erlang parameter. Using the developed equations, it was possible to define the merge capacity. To be applicable to practical uses, it was necessary to make a generalized form of the model that represents all possible volume ranges. For the generalized model, the critical gap and the shoulder lane volume are selected as the model variables based on the relationships among the shoulder lane volume, the ramp volume, and the critical gap value. As a result, the developed merge capacity model turned out to be very sensitive to the ramp volume (which represents the different traffic conditions) and the critical gap (which represents the geometric conditions of the merge areas). This model based on a shoulder lane volume and a critical gap produces several variable volumes according to the changes of traffic and geometric conditions.

A generalized model shows that the merge capacity value is on the increase as the critical gap decreases and the shoulder lane volume increases. Therefore, the merge capacity could vary according to the sizes of the shoulder lane volume and the critical gap. As a result, the merge capacity is not a fixed value but varied ones. Therefore, there need to introduce the new definition of merge capacity and to consider the variables like the ramp volume size and the critical gap which affect the merge capacity. Furthermore, this result could be applied to calculate the merge capacity reflecting the merging phenomena at ramp-freeway junction and to decide the primary parameters of on-ramp control.

It should be noted that, as a reflection of gap acceptance theory, the proposed model describes the merging phenomena for a specific geometric configuration that composes of one shoulder lane and one ramp lane. Like the US HCM methodology, the effects of the traffic conditions induced by other lanes are not taken into account. If the freeway segment is more than one lane in one direction, the traffic flow of this segment has more chances of maneuvering other lanes to avoid the conflict with the merging ramp flow. In future studies, the effects of the different number of freeway lanes on the ramp flow and the merge capacity should be studied.

ACKNOWLEDGEMENT

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### TABLE 1 Regression Statistics and Significance Test Results

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#### ANOVA

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#### t-test

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TABLE 2 Ranges of Shoulder Lane Volume by Erlang Parameter

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<td>1,306 ≤ q &lt; 1,924</td>
<td>1,924 ≤ q &lt; 2,331</td>
</tr>
</tbody>
</table>
FIGURE 2 General Diagram of Gap Acceptance Process.
FIGURE 3 Maximum Ramp Volume Defined by Shoulder Lane Volume.
FIGURE 4 Relationship between Ramp Volume and Merge Capacity (K=2).
FIGURE 5 Regression Lines for $T = 2$ and $7$.
### TABLE 3 Regression Statistics and Significance Test Results for Linear Model

<table>
<thead>
<tr>
<th>Regression</th>
<th>Multiple R</th>
<th>R^2</th>
<th>Adjusted R^2</th>
<th>Std. Error</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.95136856</td>
<td>0.90510214</td>
<td>0.90437495</td>
<td>165.762307</td>
<td>264</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ANOVA</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>Signf. F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>2</td>
<td>68399547.6</td>
<td>34199773.8</td>
<td>1244.66269</td>
<td>3.4038E–134</td>
</tr>
<tr>
<td>Residual</td>
<td>261</td>
<td>7171534.16</td>
<td>27477.1424</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>263</td>
<td>75571081.8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>t-test</th>
<th>Coefficients</th>
<th>Std. Error</th>
<th>t Stat</th>
<th>P-Value</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1757.058</td>
<td>33.963</td>
<td>51.735</td>
<td>3.26E-139</td>
<td>1690.183</td>
<td>1823.934</td>
</tr>
<tr>
<td>X Variable 1</td>
<td>0.6215588</td>
<td>0.016</td>
<td>38.683</td>
<td>4.42E-110</td>
<td>0.5899</td>
<td>0.653</td>
</tr>
<tr>
<td>X Variable 2</td>
<td>-188.238</td>
<td>5.974</td>
<td>-31.511</td>
<td>6.15E-91</td>
<td>-200.0006</td>
<td>-176.475</td>
</tr>
</tbody>
</table>
FIGURE 6 Merge Capacities Defined by Shoulder Lane Volume and Critical Gap.