A RAMP MERGE CAPACITY MODEL USING GAP ACCEPTANCE THEORY

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Abstract: Freeway merge areas are recognized as the most common segment of recurrent freeway congestion where 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 explanation for the definition of merge capacity, representing the varied nature of the merging phenomenon and the effects of merging ramp flow. The gap acceptance theory was used for this representation and Erlang distribution was selected for the definition of time headway distributions. As a result, this study has developed a model that could reflect the capacity immediately downstream of the ramp influence area based on the shoulder lane volume and the critical gap and has also discussed the effects of ramp flow and the properties of capacity.

Key Words: ramp capacity, gap acceptance, Erlang distribution, critical gap

1. INTRODUCTION

Freeways are originally conceived and designed to provide continuous, free-flow, high-speed movement of traffic on limited-access facilities. A freeway is generally perceived as the highest highway facility with full control of access and two or more lanes for the exclusive use of traffic in each direction and the only type of highway facility that provides completely "uninterrupted" flow. Although they are originally designed for uninterrupted flow, with the continuous increase of traffic demand, several locations on freeway system became congested. Among these locations, merge areas are recognized as the most common segment of recurrent freeway congestion where two separate traffic streams join to merge a single stream. The turbulence of merging movements in traffic stream affects the traffic characteristics of freeway and ramp within an influence 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 (TRB, 2000). Such turbulence in traffic flow including numerous speed 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 (TRB, 2000). 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 mathematical and theoretical methods that have 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, it has not been widely used despite its detailed reflection of traffic and road 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 (Drew *et al.*, 1967). 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 represents the random arrivals and low volume range. In addition, the authors did not any attempt to explain the influences on the merge capacity (Drew *et al.*, 1968).

In 1993, Makigami and Iizuka applied a probabilistic calculation technique for the analysis and the evaluation of weaving traffic stream, where weaving maneuvers were considered as merging maneuvers into the traffic stream (Makigami and Iizuka, 1993). Kita, on the other hand, modeled gap acceptance behavior in merging as a binary choice of "accept" and "reject." In this model, the effects of the length of acceleration lane and variation of driver behavior are described in terms of time (Kita, 1993).

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 is 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 (Elefteriadou *et al.*, 1995).

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 and 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 (Lorenz and Elefteriadou, 2001). In another study, they also employed gap acceptance theory to develop a method for the estimation of capacity of Type B weaving areas (Lorenz and Elefteriadou, 2001).

This paper addresses the need for an enhanced freeway capacity definition that incorporates the probabilistic nature of the freeway breakdown process. It consists of an extensive analysis of speed and volume data collected at two freeway bottleneck sites in Toronto, Canada. At each site, the freeway breakdown process was examined in detail for over 40 congestion events occurring during the course of nearly 20 days. The paper develops preliminary models for each site describing the probability of breakdown versus observed flow rate and examines the implications that this probabilistic approach to breakdown has on the current definition of freeway capacity. A revised, probabilistic freeway capacity definition is proposed for use in future editions of the "Highway Capacity Manual."

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 lane flow relationships are described in detail in the following sections.

2. PROPOSED MODEL STRUCTURE

The capacity of a merging 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 based upon determination of critical gap and definition of ramp capacity. The determination of critical gap reflects the geometric conditions. The parameters defining ramp capacity are shoulder lane volume, headway distribution and critical gap.

2.1. Determination of Headway Distribution

In general, time headway distribution and its shape varies for different volume states because of the increasing headway interaction within traffic flow. For example, in low traffic flow levels, there is very little headway interaction 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 maximum capacity, vehicles are in car following state.

The Pearson type III distribution is a generalized mathematical model approach to define such phenomenon, which actually is 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 ∞. 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 [May, 1990].

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 volume and K in model that can calculate K based on the volume level.

2.2. Volume Range Based on Erlang Parameter

In this study, mean and deviation of time headways distribution of the shoulder lane flow is used to define Erlang parameter (K). This relationship can be shown as follows:

$$K = \frac{m^2}{S^2} \tag{1}$$

where,
K = Erlang parameter
m = mean of time headway distribution
S^2 = deviation of time headway distribution

In case of traffic flow that have the same headway mean but different headway deviations, K takes different values: the greater the 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 various range of volumes. Data sets were collected at KwangJu and HoBub interchanges of JungBu expressway in Korea and were organized by a video image analysis system. These sites are composed of two lanes of mainline and one lane of ramp. The shoulder lanes in these sites are 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 between shoulder lane volume and Erlang parameter. The regression statistics and significance tests are shown in Figure 1 and Table 1.

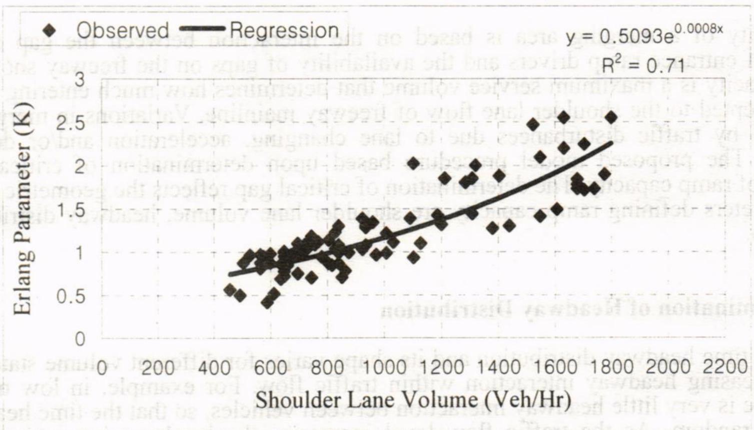

Figure 1. Relationship between Erlang Parameter and Volume

Table 1. Regression Statistics and Significance Test Results

Regression	Multiple R	R2	Adjusted R2	Std. Error	N	
	0.83992832	0.70547959	0.7019734	0.20406276	86	
ANOVA	df	SS	MS	F	Signf. F	
Regression	1	8.37868447	8.37868447	201.209436	5.1883E-24	
Residual	84	3.49789508	0.04164161			
Total	85	11.8765796				
t-test	Coefficients	Std. Error	t Stat	P-Value	Lower 95%	Upper 95%
Intercept	-0.6747	0.06083	-11.0918	3.93E-18	-0.79572	-0.55387
X Variable	2.97611	0.20981	14.18483	5.19E-24	2.558883	3.393342

As a result of the statistical analysis, an R^2 value of 0.71 and significant results from fitness tests are obtained. Using the significant coefficient of the regression analysis, K becomes:

$$K = 0.51e^{2.98q} \qquad (2)$$

where, q is the shoulder lane volume (veh/sec).

Based on relationship between K and shoulder lane volume as defined in equation (2), volume ranges for each K can be calculated. Equation (2) calculates K as a real number. Since K must be an integer in the Erlang distribution, the calculated K values are rounded to the nearest integer, which results in a volume range for each integer K.

However, K cannot be greater than 3, because of the fact that the calculated flow values will then exceed 2,300 pcphpl, the maximum capacity of a freeway lane. It is also known that the volume of shoulder lane is usually lower, because most vehicles change lanes in advance to avoid the conflict with the ramp flow. Therefore, K=1,2, and 3 represents all possible volumes of the shoulder lane. Table 2 shows the calculated volume ranges using equation (2) for K=1,2, and 3.

Table 2. Volume Range in shoulder lane by Erlang Parameter (veh/hr)

Erlang Parameter	K=1	K=2	K=3
Volume Range (vph)	0 < q < 1,306	1,306 ≤ q < 1,924	1,924 ≤ q < 2,331

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 vehicle.

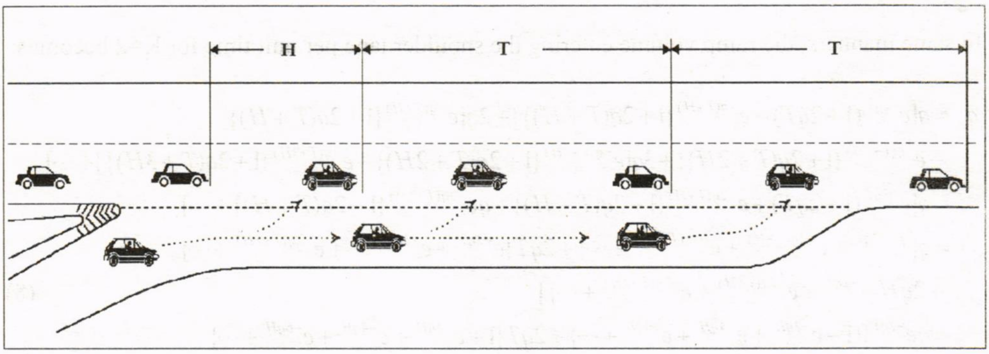

Figure 2. General Diagram of Gap Acceptance Behavior

Based on the time headway and 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 ramp volume entering the shoulder lane per unit time becomes:

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

where,
q_r = the maximum on-ramp flow (veh/sec)
q = the shoulder lane volume (veh/sec)
T = Critical Gap (sec)
H = Another critical gap for entry of additional vehicles (sec)
$P[T+iH \le t < T+(i+1)H]$ = the probability of the time headway (t) taking a value between $T+iH$ 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, $P(h \le t)$, can be expressed as follows.

$$f(t) = qe^{-qt} \tag{4}$$

$$P(h \le t) = 1 - e^{-qt} \tag{5}$$

Merging the equation (3), the probability density function and the cumulative distribution function, the ramp volume entering the shoulder lane per unit time for K=1 becomes:

$$\begin{aligned} q_r &= q[e^{-qT} - e^{-q(T+H)}] + 2q[e^{-q(T+H)} - e^{-q(T+2H)}] + \cdots \\ &= qe^{-qT} + qe^{-q(T+H)} + qe^{-q(T+2H)} + \cdots \\ &= qe^{-qT}(1 + e^{-qH} + e^{-2qH} + \cdots) \\ &= \frac{qe^{-qT}}{1 - e^{-qH}} \end{aligned} \quad (6)$$

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

$$f(t) = 4q^2 te^{-2qt}$$
$$P(h \le t) = 1 - e^{-2qt}[1 + 2qt] \quad (7)$$

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

$$\begin{aligned} q_r &= q[e^{-2qT}(1+2qT) - e^{-q(T+H)}\{1+2q(T+H)\}] + 2q[e^{-q(T+H)}\{1+2q(T+H)\} \\ &\quad - e^{-q(T+2H)}\{1+2q(T+2H)\} + 3q[e^{-q(T+2H)}\{1+2q(T+2H)\} - e^{-q(T+3H)}\{1+2q(T+3H)\}] + \cdots] \\ &= q[e^{-2qT}(1+2qT) + e^{-2q(T+H)}\{1+2q(T+H)\} + qe^{-2q(T+2H)}\{1+2q(T+H)\} + \cdots] \\ &= q[\{e^{-2qT} + e^{-2q(T+H)} + e^{-2q(T+2H)} + \cdots\} + 2qT\{e^{-2qT} + e^{-2q(T+H)} + e^{-2q(T+2H)} + \cdots\} \\ &\quad + 2qH\{e^{-2qT} + e^{-2q(T+H)} + e^{-2q(T+2H)} + \cdots\}] \\ &= qe^{-2qT}[(1 + e^{-2qH} + e^{-4qH} + e^{-6qH} + \cdots\} + 2qT\{1 + e^{-2qH} + e^{-4qH} + e^{-6qH} + \cdots\} \\ &\quad + 2qHe^{-2qH}\{1 + 2e^{-2qH} + 3e^{-4qH} + 4e^{-6qH} + \cdots\}] \\ &= qe^{-2qT}[\frac{1}{1-e^{-2qH}} + \frac{2qT}{1-e^{-2qH}} + \frac{2qHe^{-4qH}}{(1-e^{-2qH})^2}] \\ &= \frac{qe^{-2qT}}{(1-e^{-2qH})}[(1+2qT) + \frac{2qHe^{-4qH}}{(1-e^{-2qH})}] \end{aligned} \quad (8)$$

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

$$f(t) = \frac{27q^3t^2e^{-3qt}}{2}$$
$$P(h \le t) = 1 - e^{-3qt}[1 + 3qt + \frac{(3qt)^2}{2}] \quad (9)$$

and if this cumulative distribution function merges equation (3) as the same process like equations (6) and (8), the ramp flow entering the shoulder lane per unit time for K=3 becomes as follows:

$$q_r = \frac{qe^{-3qT}}{[1-e^{-3qH}]}[1 + 3qT + 4.5q^2T^2 + \frac{3qH(1+6qT)e^{-3qH}}{(1-e^{-3qH})} + \frac{9q^2H^2(1+e^{-3qH})e^{-3qH}}{(1-e^{-3qH})^2}] \quad (10)$$

Equations (4), (5), and (6) define the ramp capacities for different shoulder lane volume ranges based on 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) for the ideal and safe merge. Merge capacity can be defined as the ramp capacity and the shoulder lane volume that is used to calculate the ramp capacity are summed of ease. Next sections describe to develop an integrated merge capacity model using these ramp capacity equations above and also discuss the effect of ramp flow on the merge capacity.

3. 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 convenient 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, first step is to decide which variables should be used in the model that the model represents the merging phenomenon.

3.1. Relationship between Variables

According to equations formulated above, the 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, shoulder lane and ramp volumes are analyzed for different critical gap values. In agreement with the ramp capacity definition in section 2.3, for each critical gap value, the maximum ramp volume can't help decreasing as the shoulder lane volume increases. For smaller critical gap values, the relationship looks like almost linear. With increasing critical gap value, the relationship becomes more asymptotic and less sensitive to the high levels of shoulder lane volume. For K=2, Figure 3 simply shows such a tendency as mentioned above. For example, in Figure 3, the 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 seconds. This simply means that the probability for the ramp flow to enter the shoulder lane under these conditions is very low and then it is very difficult for the ramp vehicles to merge in this circumstance. According to Table 2, just in case the shoulder lane volume per an hour is between 1306 and 1924, Figure 3 has a meaning.

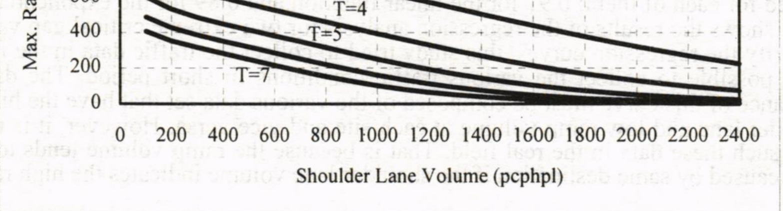

Figure 3. The Ramp Capacity under Shoulder Lane Volume (K=2)

According to equations (4), (5), and (6), the merge capacity also varies under ramp volume; the higher the ramp volume, the lower the merge capacity is. Furthermore, when the critical gap value increases, the decrease in merge capacity becomes very fast. Figure 4 illustrates the relationship between merge capacity and ramp volume for K = 2.

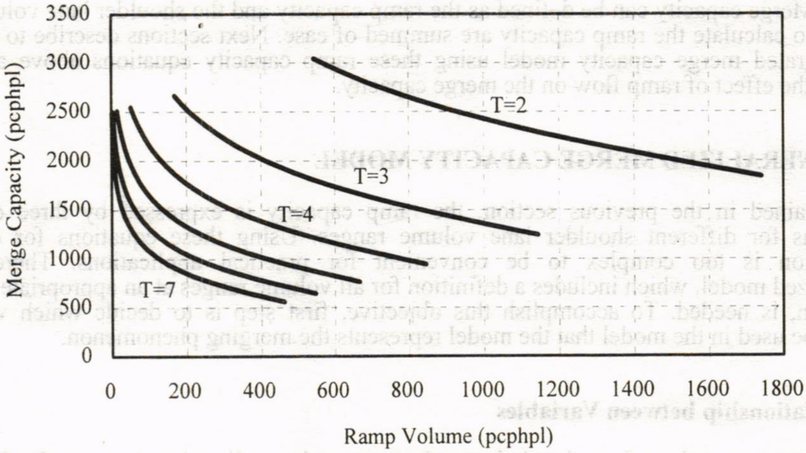

Figure 4. Relationships between Ramp Volume and Merge Capacity (K=2)

For example, in Figure 4, merge capacity shows a rapid decrease in response to a very small change in ramp volume for T = 7. However, merge capacity decrease for T = 2 is more gradual compared with T = 7. Overall, the merge of ramp vehicles to the shoulder lane flow causes lane and speed changes in shoulder lane to avoid the conflict with ramp flow. Such reactions cause turbulence and disturbance in mainline stream. Considering the effect of merging vehicles on the mainline stream, the size of the ramp volume and the critical gap value at a merge area are the most influential factors for defining merge capacity.

3.2. Development of Generalized Merge Capacity Model

Based on the relationships described in the previous section, the critical gap and the ramp volume must be selected as the model variables for merge capacity. It is known that, in real traffic conditions, it is easier to obtain the shoulder lane volume measurements compared to the ramp volume and the previous section showed that there is a relationship between shoulder lane and ramp volumes. For this reason, in this study the shoulder lane volume was used as an individual variable instead of the ramp volume. Taking the critical gap (which represents geometric conditions at a merge area) and the shoulder lane volume as independent variables, a regression analysis has performed for each critical gap from T= 2 through 7.

According to the results of the regression analysis, linear and exponential functions presented the best fit to the merging equations derived in the previous section; high R^2 values are calculated for each of them: 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 traffic conditions in short period. 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 low ramp volume at each site and vice versa. However, it is not easy to observe such these data in the real field. That is because the ramp volume tends to be a high demand caused by same destination if the shoulder lane volume indicates the high range.

When the shape of the functions are compared with results calculated by using three merging equations, linear function shows a better fit at low volume levels for T = 2, and a better fit at high volume levels for T = 7. In real traffic conditions, it is more likely to observe high volume levels if average headway value is low and low volume levels if average headway value is high. Therefore, the linear model is selected for the generalized merge capacity model. The properties of statistical analysis for the linear function are shown in Table 3.

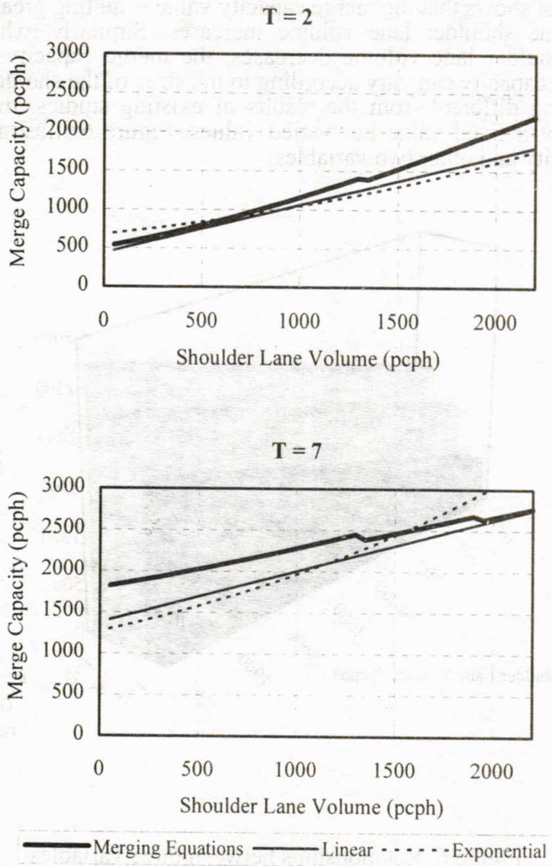

Figure 5. Regression Lines for T = 2 and 7

Table 3. Regression Statistics and Significance Test Results for Linear Function

Regression	Multiple R	R2	Adjusted R2	Std. Error	N	
	0.95136856	0.90510214	0.90437495	165.762307	264	
ANOVA	df	SS	MS	F	Signf. F	
Regression	2	68399547.6	34199773.8	1244.66269	3.4038E -134	
Residual	261	7171534.16	27477.1424			
Total	263	75571081.8				
t-test	Coefficients	Std. Error	t Stat	P-Value	Lower 95%	Upper 95%
Intercept	1757.058	33.963	51.735	3.26E-	1690.183	1823.93
X Variable 1	0.6215588	0.016	38.683	4.42E-	0.5899	0.65
X Variable 2	-	5.974	-	6.15E-	-	-

Using the values from the statistical results of regression analysis and the t-test, the generalized merge capacity model is as follows:

$$C_M = 0.621559V_S - 188.238T + 1757.058 \tag{7}$$

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 is getting greater when the critical gap decreases and the shoulder lane volume increases. Similarly, when the critical gap increases and the shoulder lane volume decreases, the merge capacity value decreases. It means that the merge capacity can vary according to the sizes of the shoulder lane volume and the critical gap. Being different from the results of existing studies, this result shows the merge capacity is not a fixed value but varied values. Figure 6 illustrates the relationship between merge capacity and other two variables.

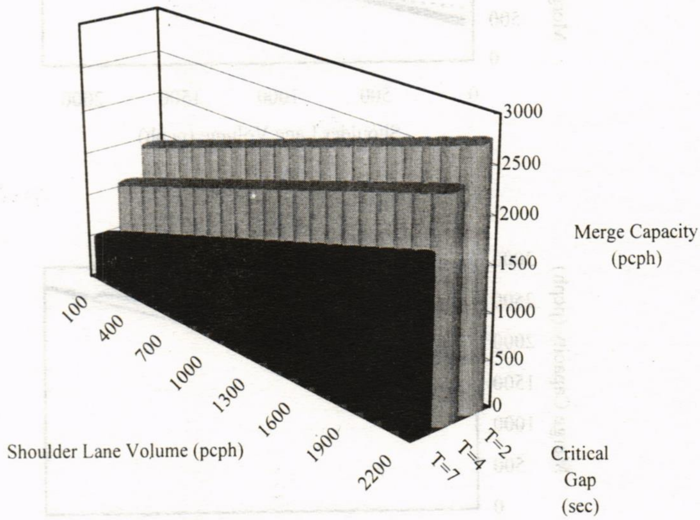

Figure 6. Relationships between three variables

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 design and control ramp metering systems. However, this methodology considered only an Erlang parameter (K=1) to cover low volume range and did not describe the effect the 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 and they proposed that the capacity could vary in some degree due to the probabilistic nature.

To find out the variation of capacity, this research tried a mathematical approach like gap acceptance process due to the difficulties of data collection that could reflect various combinations of ramp and shoulder lane flows, and also decided the variables to 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 effects two variables like the critical gap and the ramp flow on the merge capacity.

First of all, the volume ranges were defined for each Erlang parameter and then, the ramp capacity equations were derived for each Erlang parameter. Using the developed equations, it was possible to define the merge capacity. However, because these equations were used separately for practical applications, it was necessary to make a generalized 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 relationship between the shoulder lane volume, the ramp volume, and the critical gap value. As a result, the merge capacity model turned out to be very sensitive to the ramp flow (which represents the different traffic conditions) and the critical gap (which represents the geometric conditions of the ramp area). This model produces several variable volumes according to the changes of traffic and geometric conditions, which is calculated based on a shoulder volume and a critical gap.

The generalized model showed that the merge capacity value was getting greater when the critical gap decreases and the shoulder lane volume increases. For this reason, the merge capacity can 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 values. Therefore, it needs to introduce the new definition of merge capacity and to consider the variables like the ramp volume and critical gap to effect on the merge capacity in terms of traffic operation and highway design stage. Furthermore, this result can apply to improve the quality of traffic flow reflecting the practical merge capacity and to decide the primary parameters of the on-ramp control algorithm.

It should be noted that, as a reflection of gap acceptance theory, the proposed model describes the merging phenomenon for a specific geometric configuration that composes of one shoulder lane and one ramp lane. Like the HCM methodology, the effects of the traffic conditions induced by other lanes are not taken into account. When a freeway mainline segment has more than one lane, the traffic flow of this segment has more chances of maneuvering 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 merge capacity should be studied.

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