■ 論 文 ■

Model Development Determining Probabilistic Ramp Merge Capacity Including Forced Merge Type

강제합류 형태를 포함한 확률적 연결로 합류용량 산정 모형 개발

KIM, Sang Gu
(Assistant Professor, Yosu National University)

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Key Words : Critical Gap, Erlang Parameter, Ramp Merge Capacity, Forced Merge, Gap Acceptance Theory

요 약

수십년동안 합류부 교통특성 및 현상을 다루는 많은 연구가 있어 왔지만 합류부 교통류를 평가하는 분석방법론은 그리 많이 개발되지 않았고 특히 합류용량에 대한 연구는 거의 이루어지지 않았었다. 본 연구는 합류부에서 강제합류를 포함한 합류용량을 확률적으로 결정하는 모형 개발을 목적으로 수행되었다. 고속도로 본선 바깥차로의 시간차두간격 분포를 Erlang 분포로 가정하고 간격수락이론을 이용하여 합류용량 산정 모형식을 개발하였고, 이때 본선 차두간격이 임계간격보다 작은 경우 발생되는 강제합류 형태가 용량 산정식에 반영되었다. 또한, 합류용량 모형식에서 중요한 변수로 사용되는 임계간격을 결정하고자 연결로에서 진입하는 개별차량의 합류행태를 조사하여 회귀분석을 통한 모형식을 구축하였다. 개발된 용량식을 토대로 합류용량 값들을 도로 및 교통조건에 따라 제시하였는데 임계간격 크기가 커지고 연결로 진입교통량이 많아질수록 합류용량은 적게 산출되었다. 이러한 합류용량 값의 변화는 기존 HCM 방법에서 제시하고 있는 하나의 고정된 용량 값과는 다른 결과로 해석되고, 변화하는 합류용량 값은 앞으로 연결로 접속부 교통운영에서 고려해야 할 주요한 파라메타라고 생각된다.

Ⅰ. 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, ramp merge areas are recognized as the most common segment of recurrent freeway congestion because two separate traffic streams join to merge a single stream. The interference of merging movements in the traffic stream may affect the traffic characteristics of freeway and ramp junction.

As noted in US Highway Capacity Manual (HCM), this influence area extends to a distance of 450 meters including acceleration lane at the downstream of an on-ramp. However, there is no evidence that merging maneuvers restrict the total capacity of the downstream basic freeway segments. Their influence is primarily to add or subtract demand at the ramp-freeway junction. Thus, the capacity of a downstream basic freeway segment is not influenced by turbulence in a merge area. The capacity will be the same as if the segment were a basic freeway segment. As on-ramp vehicles enter the freeway at a merge area, the total number of ramp and approaching freeway vehicles that can be accommodated is the capacity of the downstream basic freeway segment (TRB, 2000).

Over the decades, several studies have been attempted to explain and analyze the 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. It is described in US HCM that the methodology for the freeway-ramp junctions 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. However, this method does not take any direct relationship between the ramp and the freeway mainline flows into consideration, though this relationship strongly affects ramp merge capacity within this area. Furthermore, it is proposed that capacity for a merge area has some fixed values, where only free-flow speed and the number of lanes in one direction are taken into account disregarding any influences of on-ramp merging flow.

Another approach for analyzing the traffic characteristics of a merge area is the gap acceptance theory, which is based on the mathematical and theoretical method that had mainly been studied during the 1960s. In comparison to HCM methodology, the gap acceptance theory is characterized by the relationship between the ramp and the freeway flows that can consider the influences caused by on-ramp vehicles. It also makes it possible to take the critical gap for roadway conditions and the headway distribution for traffic conditions into account. However, due to the complexity of the model and the difficulties in validation the gap acceptance approach has not been widely used in spite of its strong consideration of the influences of on-ramp flow.

In the 1960s, Drew et al. (1967) developed theoretical models and parameters for freeway merging process and established a statistical relationship between the percent gap acceptance and gap size. This relationship was applied to single and multiple entry merge areas. Drew et al. (1968), then, presented a new approach to determine merge capacity using gap acceptance behavior of the drivers and applied this approach to freeway design and control such as ramp metering systems. The influences of on-ramp design characteristics, such as the acceleration lane length, the 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, they made use of only single Erlang parameter (K=1) for the negative exponential distribution that represented the random arrival patterns of low flow level. In addition, no attempt has been made to explain the influences of on-ramp flow on the merge capacity.

Recently, Kim et al. (2001) extended the gap acceptance theory to develop the model that could determine merge capacity represented up to Erlang parameter of 3 considering only ideal merge type at a merge area with one lane freeway and one lane ramp and described the relationships among the merge capacity, the critical gap, and the shoulder lane volume. In addition, Kim and Son (2003) attempted to explain the effects of on-ramp flow on merge capacity using the developed model and it was presented in their study that merge capacity would be affected by on-ramp flow and that capacity value could be varied by the ramp volume and the critical gap. In consequence, it should be noted that merge capacity is not a fixed value but varied ones and there is needed to consider the variables like the ramp volume and the critical gap that affect merge capacity.

In association with the probabilistic natures of breakdown and capacity, Elefteriadou et al. (1995) 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.

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 (2001). 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".

To deal with traffic phenomena in merge areas, Kita (1999) developed a game theory model to describe the traffic behavior of a pair of merging and through vehicles in merging sections, while explicitly considering the interaction between them. It means that both the merging and through vehicles attempt to take the best actions for themselves by forecasting the other's action, respectively. His approach, in describing a traffic phenomenon as a game, has the advantage of making a simpler model by separating the direct and indirect influences.

The objective of this study is to develop the model that can determine probabilistic ramp merge capacity including forced merge type at a merge area with multi-lane freeway and one lane ramp and to propose ramp merge capacity under the various conditions of traffic flow. To achieve this objective, this study makes use of gap acceptance theory and Erlang distribution as the time headway distribution. This study deals with three major steps: determination of probability distribution function standing for the time headway distribution, derivation of ramp merge capacity equations by considering the relationships between ramp and shoulder lane flows, and the regression analysis to determine the critical gap. Based on ramp merge capacity determined by using developed models the characteristics of merging capacity are described in this paper.

II. Time Headway Distribution

1. Probability Distribution Model

In general, the shape of the time headway distribution varies as the traffic flow rate increases because of the increasing interactions between vehicles in the traffic stream. For example, under very low flow conditions, there are very little interactions between the vehicles and the time headways appear to be somewhat random. As the traffic flow level increases, there are increasing interactions between vehicles. As the traffic flow level approaches capacity, almost all vehicles are interacting and are in a car-following process.

The Pearson type III distribution is a generalized mathematical model approach to define such phenomena and is actually a family of distribution models that can be telescoped down into a nested subset of simpler distribution models. This model becomes the simple Erlang distribution when the shift parameter, α, takes zero value and shape parameter that is called the Erlang 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 resulting distribution takes the form of a negative exponential (random) distribution. As the K value selected approaches infinity, the resulting distribution approaches a constant headway distribution (May, 1990).

Following the assumption that the Erlang distribution represents the time headway distribution, the selection of shape parameter, K, gains an ultimate importance. It is known that K is affected by road alignments, grade, and other environmental factors; however, the most influential factor is the traffic flow level. Therefore, the relationship between the Erlang parameter (K) and the traffic flow rate should firstly be defined in this study.

2. Erlang Parameter (K)

According to Reference (9), the mean and the standard deviation of time headway distribution in the traffic stream are used to estimate an approximate Erlang parameter (K) and their relationship can be given by the equation

$$K = \frac{\bar{t}}{s} \tag{1}$$

where

K : Erlang parameter (in positive integer value)

$\bar{t}$: the mean time headway (sec)

s : the standard deviation of the measured time headway distribution (sec)

In case two time headway distributions have the same mean time headway but different standard deviations, Erlang parameter takes different values each other: the greater the standard deviation, the smaller the Erlang parameter is. This simply means that the interactions between vehicles are getting weaker.

The data set of time headway was obtained in the shoulder lanes at two merge areas in Korea and then Erlang parameters were calculated using Equation (1). Taking the shoulder lane volume (q) as an independent variable, the regression analysis was performed to define the Erlang parameter (K).

Using the significant coefficient of the regression analysis, the regression model becomes:

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

where
q : the shoulder lane volume (veh/sec)

Based on the Equation (2), the volume ranges to each Erlang parameter (K) can be defined. This means that the Erlang parameter defined represents the range of volume. 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 Elang parameter (K) is defined as shown in ⟨Table 1⟩.

⟨Table 1⟩ Volume Ranges defined by the Values of Erlang Parameter (K)

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

It is not needed in this study that the value of Erlang parameter is greater than 3. If Erlang parameter (K) is greater than 3, the volume range will exceed 2,300 vph that is generally perceived as capacity value on a freeway basic section. It is also known that the shoulder lane volume is usually lower than those of other lanes, because most vehicles change to inner lane in advance to avoid the conflict with the ramp merging flow entering freeway. Therefore, the Erlang parameters of 1, 2, and 3 can cover all possible volume ranges that the time headway distribution appears in the shoulder lane.

III. Ramp Merging Process

Ramp capacity at a merge area is based on the interaction between the gap acceptance behaviors of on-ramp drivers and the availability of gaps provided by the flow of freeway shoulder lane. Ramp merge capacity is a possible volume that indicates how many on-ramp vehicles can be accepted into the flow of freeway mainline. Ramp merging process includes the various behaviors of drivers on ramp or on freeway at a merge area. Behaviors of freeway drivers in ramp merging process are divided into three types such as lane changing to the inner lane, acceleration and deceleration on the shoulder lane.

1. Merging Behaviors

It is known that there are two merge types such as an ideal and a forced merges when a ramp vehicle enters the right most lane of freeway mainline. Such merge types can be distinguished by the variable called the critical gap. If a ramp vehicle enters in the shoulder lane using the gap that is greater than any given critical gap, it is called the ideal merge and it is assumed that the ramp-merging vehicle may not affect freeway flow, so that there are no effects on freeway vehicles traveling on the shoulder lane. To the contrary if the ramp merging vehicle makes use of the gap that is smaller than any given critical gap, the ramp merging vehicle could have an influence on the freeway flow and a following freeway vehicle behind the merged ramp vehicle must react abrupt behaviors like lane-changing and speed-changing to avoid conflicts with the ramp merged vehicle and this merge type is called forced merge.

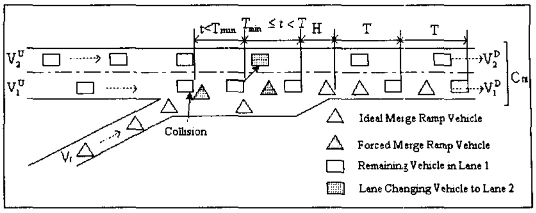
In general the critical gap is defined as the average value of gaps that ramp vehicles have selected among the gaps provided by the traffic stream. Getting the greater critical gap means that the driver of ramp vehicle wants bigger gap to safely merge in the traffic stream of freeway. For instance, the driver of ramp vehicle may need a greater critical gap if the acceleration lane length is short and the design speed of ramp is low. It is known that the critical gap is related to road conditions.

The critical gap can be considered as a parameter that can decide the merging type. Therefore, it is very important to decide the adequate critical gap in accordance with a freeway-ramp junction.

If the gap over the critical gap is provided in the flow of shoulder lane, a ramp vehicle can merge smoothly without any conflicts with any vehicles traveling in the shoulder lane and the vehicles of the shoulder lane can keep moving with maintaining their own gaps. However, if the gap under the critical gap is provided, the driver of merging vehicle must choose a behavior of either giving up merging or merging forcedly. In case the ramp vehicle tries to merge forcedly the vehicles in the shoulder lane unavoidably have to take any movement like lane changing or deceleration. Such a movement would directly affect the upstream flow of shoulder lane and its inner lane, so that it might result in breakdown near a merge area.

⟨Figure 1⟩ shows a general ramp merging process at a merge area in which has a directional 2 lanes freeway and a lane ramp. Here, Lane 1 is a shoulder lane and Lane 2 is the inner lane of shoulder lane. In addition, T_M is the merging 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 the next merging vehicles that consecutively follow the leading merging vehicle using a same gap. Another critical gap of H is usually smaller than the critical gap of T_M and is supposed to be half of the critical gap under ideal conditions.

The effects of ramp merging vehicles on the flow of Lane 2 are restricted to the forced merge type. Because such a forced merge could result in the lane-changing of a following vehicle traveling in Lane 1. The forced merge type can be divided into two cases: one is for the case that a ramp vehicle tries to merge Lane 1 using the gap that



⟨Figure 1⟩ Ramp Merging Process Diagram

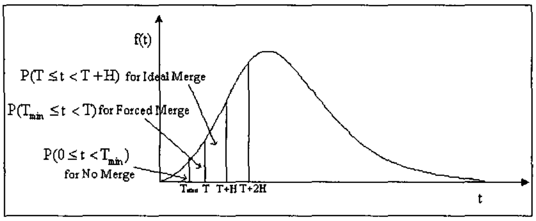
is between the minimum critical gap (T_{min}) and T_M and the other is for the case that a ramp vehicle tries to enter Lane 1 using the gap that is less than T_{min}. The first case may cause the lane-changing or the deceleration of a following vehicle in Lane 1 and the second case may break out an accident because the following freeway vehicle cannot avoid colliding with the ramp vehicle that abruptly merges into Lane 1. In this study the second case will not be considered because this study focuses on determining capacity in stable flow state.

2. Ideal Merge Type

As described in previous section, now that the behavior of ideal merge just makes use of a gap that is great than a critical gap (T_M) for merging it is supposed that there is no influence on the flow of shoulder lane. Considering that a merging behavior is an ideal merge type, based on the time headway in Lane 1 and the critical gap (T_M), the possibility of ramp vehicles to enter the shoulder lane can be described as follows:

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

Supposed that the probability density function (PDF) is f(t), the probability of the time headway (t) taking a value that is less than the critical gap (T_M) can be denoted as $P[t<T_M]$ that is a



〈Figure 2〉 Probability Density Function

cumulative density function. This probability is the same as the probability that no ramp vehicle enters under the ideal merge. And the probability that only one vehicle can enter is $P[T_M \le t < T_M + H]$ as shown in 〈Figure 2〉. Therefore, the probabilities that the ramp vehicles of n can enter under certain ranges of the time headway (t) can be defined in sequence. If the time headway (t) is between T_M and T_M+H, the number of ramp vehicles entering Lane 1 for the ideal merge can be obtained by multiplying the probability of $P[T_M \le t < T_M + H]$ and and the volume of lane 1 (V_l^U) and is expressed by the equation $V_r^I = V_l^U \times P[T_M \le t < T_M + H]$.

Hence, the possible ramp volume entering Lane 1 smoothly that is the shoulder lane per unit time becomes:

$$V_r^I = V_l^U \sum_{i=0}^{\infty} (i+1) \cdot P_l[T_M + iH \le t < T_M + (i+1)H] \quad (3)$$

where

V_r^I : the maximum ramp volume in ideal merge (veh/sec)

V_l^U : the volume of Lane 1 at upstream merge area (veh/sec)

T_M : the critical gap for merging (sec)

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

$P_l[T_M + iH \le t < T_M + (i+1)H]$: the probability of the time headway (t) of Lane 1 taking a value between $T_M + iH$ and $T_M + (i+1)H$.

3. Forced Merge Type

It is supposed that the minimum critical gap that a ramp merging vehicle can enter without collision with the following vehicle in Lane 1 is denoted as T_{min} and is greater than another critical gap (H). This means that this forced merge type happens in only single entry merge.

If the passing time headway, t, is between T_{min} and critical gap (T_M), one ramp vehicle tries to enter Lane 1 forcedly as shown in 〈Figure 1〉 and this possible ramp volume (V_r^F) for the forced merge type becomes:

$$V_r^F = V_l^U \times P_l[T_{min} \le t < T_M] \quad (4)$$

If a ramp vehicle tries to merge using the gap that is between T_{min} and critical gap (T_M), a following vehicle in Lane 1 must change to Lane 2 or decelerate its speed to avoid the conflict with the ramp-merging vehicle. In case of the lane-changing, the volume of lane changing to Lane 2, V_{LC}, will be a part of the total ramp volume entering Lane 1. Whether the following vehicle in Lane 1 can change from Lane 1 to Lane 2 depends on the availability of gap provided by the flow of Lane 2. If the critical gap for lane changing is denoted as T_{LC}, the volume of lane changing to Lane 2 (V_{LC}) can be given as the following equation.

$$V_{LC} = V_l^U \times P_l[T_{min} \le t < T_M] \times P_2[t \ge T_{LC}] \quad (5)$$

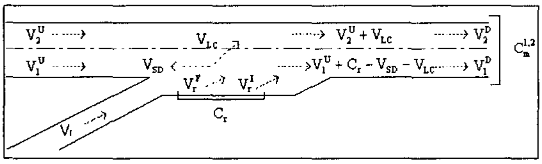
Here, $P_2[t \ge T_{LC}]$ means the probability that the passing time headway (t) of Lane 2 is greater than T_{LC}.

If the gap provided by the flow of Lane 2 is not great enough to change lane, the following vehicle in Lane 1 must be slow down to avoid colliding with ramp merging vehicle. The decelerating volume in Lane 1 is the same as the remaining volume not to change to Lane 2.

$$\begin{aligned} V_{SD} &= V_l^U \times P_l[T_{min} \le t < T_M] \times P_2[0 \le t < T_{LC}] \\ &= V_l^U \times P_l[T_{min} \le t < T_M] \times (1 - P_2[t \ge T_{LC}]) \quad (6) \end{aligned}$$

4. Maximum Ramp Merge Volume

According to US HCM of 2000, it is addressed that the maximum ramp merge volume is the summation of Lane 1, Lane 2 and ramp volumes at an upstream merge area and it is the same as the volumes of Lane 1 and Lane 2 at a downstream merge area as shown in ⟨Figure 3⟩.



⟨Figure 3⟩ Ramp Merge Volume for 2-Lane Freeway

The volume of Lane 2 (V_2^D) at the downstream merge area is the summation of the upstream volume of Lane 2 (V_2^U) and the volume of lane changing (V_{LC}).

$$V_2^D = V_2^U + V_{LC} \tag{7}$$

In addition, the volume of Lane 1 at downstream merge area can be arranged as follows.

$$\begin{aligned} V_1^D &= V_1^U + V_r^I + V_r^F - V_{LC} \\ &= V_1^U + V_r^I + (V_1^U \times P_1[T_{min} \le t < T_M]) \\ &+ (V_1^U \times P_1[T_{min} \le t < T_M] \times P_2[t \ge T_{LC}]) \\ &= V_1^U + V_1^U \sum_{i=0}^{\infty} (i+1) \cdot P_1[T + iH \le t < T + (i+1)H] \\ &+ (V_1^U \times P_1[T_{min} \le t < T_M]) \times (1 + P_2[t \ge T_{LC}]) \end{aligned} \tag{8}$$

The both volumes of Lane 1 and Lane 2 at a downstream merge area is the sum of V_1^D and V_2^D, and these volumes are the same as the maximum volume which can be accommodated in both Lane 1 and Lane 2.

$$\begin{aligned} V_{1,2}^D &= V_1^D + V_2^D \\ &= V_1^U + V_r^I + V_r^F - V_{LC} + V_2^U + V_{LC} \\ &= V_1^U + V_2^U + V_r^I + V_r^F \\ &= V_1^U + V_2^U + V_1^U \sum_{i=0}^{\infty} (i+1) \cdot P_1[T + iH \le t < T + (i+1)H] \\ &+ (V_1^U \times P_1[T_{min} \le t < T_M]) \end{aligned} \tag{9}$$

This volume ($V_{1,2}^D$) is the same as the maximum volume that can be accommodated within mainline freeway of Lanes 1 and 2 downstream influenced by ramp merging flow at a freeway-ramp junction and is called ramp merge capacity.

IV. Formulation of Ramp Merge Capacity

1. Ramp Capacity Equation

Supposed a single, inexhaustible queue waiting to enter in the traffic stream of Lane 1, ramp capacity (C_r) is defined by the possible ramp volumes in both ideal and forced merge types, and these volumes can be expressed with Equations (3) and (4).

$$\begin{aligned} C_r &= V_r^I + V_r^F \\ &= V_1^U \sum_{i=0}^{\infty} (i+1) \cdot P_1[T_M + iH \le t < T_M + (i+1)H] \\ &+ V_1^U \times P_1[T_{min} \le t < T_M] \end{aligned} \tag{10}$$

To formulate Equation (10) it is supposed that the time headway distribution of Lane 1 is represented by Erlang distribution and Equation (10) is derived for each Erlang parameter (K=1, 2, 3) as defined previously.

Firstly, considering that the negative exponential distribution for K=1 represents the time headway distribution of Lane 1, the probability density function (PDF), f(t), and the cumulative distribution function (CDF), $P_1(t \ge h)$, can be given as follows.

$$f(t) = V_1^U e^{-V_1^U t}, \quad P_1(t \ge h) = e^{-V_1^U h} \tag{11}$$

Merging Equations (3) and (11), the maximum ramp volume for the ideal merge type entering

Lane 1 per unit time becomes:

$$V_r^I = V_1^U[e^{-V_1^UT} - e^{-V_1^U(T+H)}] + 2V_1^U[e^{-V_1^U(T+H)} - e^{-V_1^U(T+2H)}] + \cdots$$
$$= V_1^U e^{-V_1^UT} + V_1^U e^{-V_1^U(T+H)} + V_1^U e^{-V_1^U(T+2H)} + \cdots$$
$$= V_1^U e^{-V_1^UT}(1 + e^{-V_1^UH} + e^{-2V_1^UH} + \cdots)$$
$$= \frac{V_1^U e^{-V_1^UT}}{1 - e^{-V_1^UH}} \qquad (12)$$

In addition, merging Equations (4) and (11), the forced ramp volume entering Lane 1 per unit time becomes:

$$V_r^F = V_1^U[e^{-V_1^UT_{min}} - e^{-V_1^UT_M}] \qquad (13)$$

Using Equation (10), ramp capacity that means the maximum ramp volume entering Lane 1 for both merge types becomes:

$$C_r^{K=1} = \frac{V_1^U e^{-V_1^UT}}{1 - e^{-V_1^UH}} + V_1^U[e^{-V_1^UT_{min}} - e^{-V_1^UT_M}] \qquad (14)$$

For the Erlang parameter (K) of 2, the probability density function, f(t), and the cumulative distribution function, $P_1(t \geq h)$, are:

$$f(t) = 4V_1^{U^2} te^{-2V_1^Ut}, \quad P_1(t \geq h) = e^{-2V_1^Uh}[1 + 2V_1^Uh] \qquad (15)$$

In same manners, the maximum ramp volume entering Lane 1 per unit time for the ideal merge type becomes:

$$V_r^I = \frac{V_1^U e^{-2V_1^UT_M}}{(1 - e^{-2V_1^UH})}[(1 + 2V_1^UT_M) + \frac{2V_1^U He^{-4V_1^UH}}{(1 - e^{-2V_1^UH})}] \qquad (16)$$

And the forced ramp volume entering Lane 1 is:

$$V_r^F = V_1^U \times [e^{-2V_1^UT_{min}}(1 + 2V_1^UT_{min})$$
$$^{-2V_1^UT_M}(1 + 2V_1^UT_M)] \qquad (17)$$

Therefore, ramp capacity for Erlang parameter of 2 becomes:

$$C_r^{K=2} = \frac{V_1^U e^{-2V_1^UT_M}}{(1 - e^{-2V_1^UH})}[(1 + 2V_1^UT_M) + \frac{2V_1^U He^{-4V_1^UH}}{(1 - e^{-2V_1^UH})}]$$
$$+ V_1^U \times [e^{-2V_1^UT_{min}}(1 + 2V_1^UT_{min}) - e^{-2V_1^UT_M}(1 + 2V_1^UT_M)] \qquad (18)$$

Finally, for the Erlang parameter (K) of 3, the probability density function, f(t), and the cumulative distribution function, $P_1(t \geq h)$, are:

$$f(t) = \frac{27V_1^{U^3}t^2e^{-3V_1^Ut}}{2},$$
$$P_1(t \geq h) = e^{-3qh}[1 + 3qh + \frac{(3qh)^2}{2}] \qquad (19)$$

If this cumulative distribution function merges in Equation (3) as the same process like Equations (12) and (16), the maximum ramp volume entering Lane 1 per unit time for K=3 becomes:

$$V_r^I = \frac{V_1^U e^{-3V_1^UT_M}}{[1 - e^{-3V_1^UH}]}[1 + 3V_1^UT_M + 4.5V_1^{U^2}T_M^2$$
$$+ \frac{3V_1^UH(1 + 6V_1^UT_M)e^{-3V_1^UH}}{(1 - e^{-3V_1^UH})}$$
$$+ \frac{9V_1^{U^2}H^2(1 + e^{-3V_1^UH})e^{-3V_1^UH}}{(1 - e^{-3V_1^UH})^2}] \qquad (20)$$

$$V_r^F = V_1^U \times [e^{-3V_1^UT_{min}}(1 + 3V_1^UT_{min} + 4.5V_1^{U^2}T_{min}^2)$$
$$- e^{-3V_1^UT_M}(1 + 3V_1^UT_M + 4.5V_1^{U^2}T_M^2)] \qquad (21)$$

$$C_r^{K=3} = \frac{V_1^U e^{-3V_1^UT_M}}{[1 - e^{-3V_1^UH}]}[1 + 3V_1^UT_M + 4.5V_1^{U^2}T_M^2$$
$$+ \frac{3V_1^UH(1 + 6V_1^UT_M)e^{-3V_1^UH}}{(1 - e^{-3V_1^UH})}$$
$$+ \frac{9V_1^{U^2}H^2(1 + e^{-3V_1^UH})e^{-3V_1^UH}}{(1 - e^{-3V_1^UH})^2}]$$
$$+ V_1^U \times [e^{-3V_1^UT_{min}}(1 + 3V_1^UT_{min} + 4.5V_1^{U^2}T_{min}^2)$$
$$- e^{-3V_1^UT_M}(1 + 3V_1^UT_M + 4.5V_1^{U^2}T_M^2)] \qquad (22)$$

According to ⟨Table 1⟩, each Equation of (14), (18) and (22) means ramp capacity (C_r) that covers different volume ranges of Lane 1 (V_l^U). Since Erlang parameter is changeable by the shape of Erlang distribution that represents the time headway distribution of Lane 1 it is important to decide an appropriate Erlang parameter that can represent the characteristics of time headway distribution in Lane 1. For instance, Equation (18) can be used in case the volume of Lane 1 is between 1,306 and 1,924 vph for Erlang parameter of 2. The following section deals with formulating merge capacity equation using the ramp capacity equations above.

2. Merge Capacity Equation

As described in the previous section, merge capacity could be obtained from the volumes of Lane 1 and Lane 2 at the downstream merge area and this value of capacity is the same as the maximum merge volume that can be accommodated reflecting the ramp volume entering downstream Lanes 1 and 2.

Therefore, merge capacity is defined as Equation (9) and this can be expressed again using ramp capacity formulated above.

$$\begin{aligned} C_m^{1,2} &= V_l^D + V_2^D \\ &= V_l^U + V_r^I + V_r^F - V_{LC} + V_2^U + V_{LC} \\ &= V_l^U + V_2^U + V_r^I + V_r^F = V_l^U + V_2^U + C_r \end{aligned} \tag{23}$$

For the Erlang parameter of 1, substituting the ramp capacity (C_r) of Equation (23) for Equation (14) merge capacity becomes:

$$C_m^{K=1} = V_l^U + V_2^U + \frac{V_l^U e^{-V_l^U T}}{1 - e^{-V_l^U H}} + V_l^U [e^{-V_l^U T_{min}} - e^{-V_l^U T_M}] \tag{24}$$

In same manners, merge capacities for Erlang parameters of 2 and 3 are:

$$\begin{aligned} C_m^{K=2} = V_l^U + V_2^U + &\frac{V_l^U e^{-2V_l^U T_M}}{(1 - e^{-2V_l^U H})} \\ &[(1 + 2V_l^U T_M) + \frac{2V_l^U He^{-4V_l^U H}}{(1 - e^{-2V_l^U H})}] \\ &+ V_l^U \times [e^{-2V_l^U T_{min}} (1 + 2V_l^U T_{min}) \\ &- e^{-2V_l^U T_M} (1 + 2V_l^U T_M)] \end{aligned} \tag{25}$$

$$\begin{aligned} C_m^{K=3} = V_l^U + V_2^U + &\frac{V_l^U e^{-3V_l^U T_M}}{[1 - e^{-3V_l^U H}]} [1 + 3V_l^U T_M + 4.5 V_l^{U^2} T_M^2 \\ &+ \frac{3V_l^U H(1 + 6V_l^U T_M) e^{-3V_l^U H}}{(1 - e^{-3V_l^U H})} \\ &+ \frac{9V_l^{U^2} H^2 (1 + e^{-3V_l^U H}) e^{-3V_l^U H}}{(1 - e^{-3V_l^U H})^2}] \\ &+ V_l^U \times [e^{-3V_l^U T_{min}} (1 + 3V_l^U T_{min} + 4.5 V_l^{U^2} T_{min}^2) \\ &- e^{-3V_l^U T_M} (1 + 3V_l^U T_M + 4.5 V_l^{U^2} T_M^2)] \end{aligned} \tag{26}$$

V. Calculation of Ramp Merge Capacity

1. Ramp Capacity

To use the equations for ramp merge capacity, it is needed that some parameters are calibrated by investigating field data in real world. These parameters are here the critical gap for merging (T_M), another critical gap for multi-entry (H), and the minimum critical gap (T_{min}). However, the equations derived in this study are just tested to see if they have the meaning values after assuming the parameters used in the equation. Supposed that another critical gap (H) is the half of the critical gap (T_M) and the minimum critical gap (T_{min}) is 2 seconds, ramp merge capacity can be calculated under various conditions of the critical gap and the volumes of Lane 1 and Lane 2. For instance, if the critical gap for merging is defined as 4 seconds and the volumes of Lane 1 and Lane 2 are both 1,400 vph, the possible ramp volume entering Lane 1 is 838 vph and ramp merge capacity is calculated as 3,638 vph using Equation (25).

〈Table 2〉 Ramp and Merge Capacities by Critical Gap

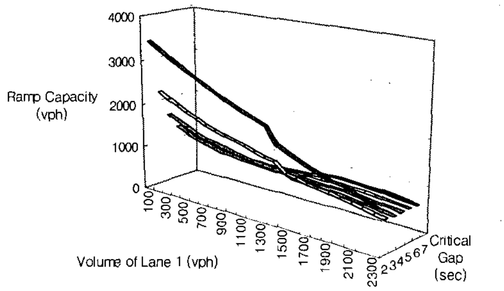
Lane 1 (vph)	Lane 2 (vph)	Ramp Capacity (vph)			Merge Capacity (vph)			Used Equations
		T_M=2	T_M=4	T_M=6	T_M=2	T_M=4	T_M=6	
200	200	3312	1542	969	3712	1942	1369	(24)
400	400	3046	1351	839	3846	2151	1639	
600	600	2800	1209	770	4000	2409	1970	
800	800	2574	1101	735	4174	2701	2335	
1000	1000	2366	1017	719	4366	3017	2719	
1200	1200	2173	950	711	4573	3350	3111	
1400	1400	1729	838	764	4529	3638	3564	(25)
1600	1600	1510	800	755	4710	4000	3955	
1800	1800	1321	760	733	4921	4360	4333	
2000	2000	1215	714	706	5215	4714	4706	(26)
2200	2200	1016	645	640	5416	5045	5040	

〈Table 2〉 shows that ramp capacity and merge capacity are calculated by using Equations (24), (25) and (26) under various volumes of Lane 1 and Lane 2 and the critical gaps of 2, 4, and 6. Here, the equations used are classified by the volume range for each Erlang parameter in 〈Table 1〉.

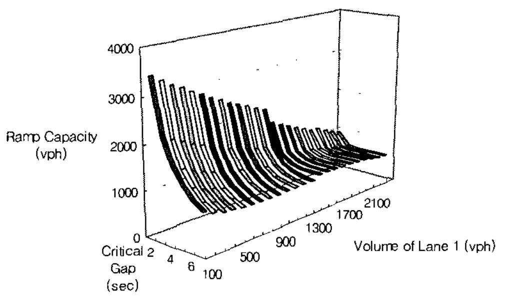
According to 〈Table 2〉, ramp capacity trends to decrease with same critical gap as the volume of Lane 1 increases and it is shown that as the critical gap increases ramp capacity decreases. In addition, ramp merge capacity increases as the critical gap decreases and the volume of Lane 1 increases.

As shown in 〈Figure 4〉, ramp capacity decreases as the volume of Lane 1 increases for each critical gap value. For smaller critical gap values, it is obvious to have a tendency to be in the rapid decrease while there is a gentle decrease as the volume of Lane 1 increases, especially in case of the great critical gap like 7. According to the result of 〈Table 1〉, the following 〈Figure 4〉 and 〈Figure 5〉 are divided into 3 regimes and each regime coincides with the volume boundary of Lane 1 defined by each Erlang parameter.

In 〈Figure 5〉 it is shown that ramp capacity becomes decreased as the critical gap increases and such a tendency becomes diminished as the volume of Lane 1 becomes greater.



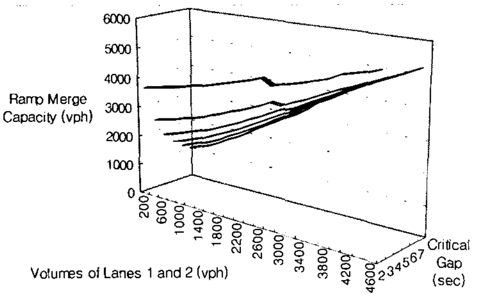
〈Figure 4〉 Ramp Capacity by the Volume of Lane 1



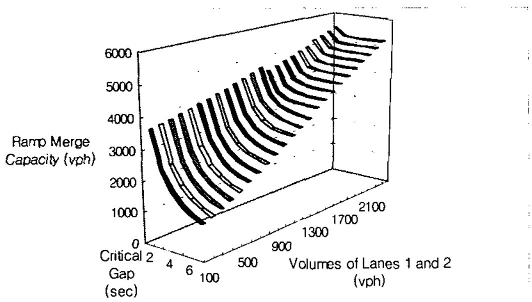
〈Figure 5〉 Ramp Capacity by Critical Gaps

2. Merge Capacity

〈Figure 6〉 shows the relationships between merge capacity (C_m) and the volumes of Lanes 1 and 2 ($v_1^U + v_2^U$) to each critical gap (T_M). In this figure merge capacity increases as the Lanes 1 and 2 volumes increase under the same critical



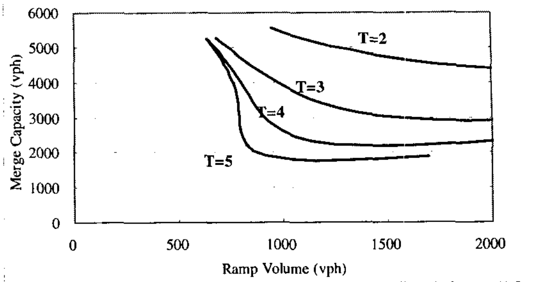
〈Figure 6〉 Ramp Merge Capacity by Volumes of Lane 1 and 2



〈Figure 7〉 Ramp Merge Capacity by Critical Gaps

gap. 〈Figure 7〉 also shows that merge capacity decreases as the critical gap increases under same volume summation of Lanes 1 and 2.

〈Figure 8〉 illustrates the relationship between merge capacity and the ramp volume for Erlang parameter (K) of 2. According to 〈Figure 8〉, merge capacity becomes smaller as the ramp volume increases; the higher the ramp volume, the lower merge capacity is. Furthermore, as the critical gap increases, merge capacity decreases very rapidly. For instance, merge capacity for the critical gap (T) of 4 shows a rapid decrease in response to a very small change of the ramp volume. However, merge capacity of T=2 is more gradual decreased compared with the other greater critical gap. In addition, in case of the critical gap of 5 it is shown that merge capacity increases nearly longitudinally around the ramp volume of 790 vph. With the same ramp volume, it is shown that merge capacity has different values by the sizes of critical gap. It means that merge capacity could vary though



〈Figure 8〉 Relationship between Merge Capacity and Ramp Volume for K=2

the ramp volume is same.

Ramp vehicles entering the flow of Lane 1 may result in the lane-changing and speed-changing in the stream of Lane 1. These behaviors of lane-changing and speed-changing may break down the flows of Lane 1 and Lane 2 and then affect the decrease of merge capacity.

Considering the effect of ramp merging vehicles on the mainline stream, the ramp volume and the critical gap are the most influential factors for defining ramp merge capacity.

3. Determination of Critical Gap

To calculate the critical gap (T_M) with ease, this study has performed a regression analysis using field data and two variables of the merging distance (D) and the speed (S_r) of ramp vehicle were selected as independent variables for the regression model of critical gap.

The traffic data used in this study were collected at three freeway-ramp terminals, which have one directional 2-lane mainline and one-lane entrance ramp. These sites are KwangJu and Hobub interchanges on JungBu Expressway and Seohanam interchange on Seoul Outer Ring Expressway in Korea. The collected items are the speed of individual vehicle along the acceleration lanes, the locations of the merging points, the vehicle counts, and the accepted gaps on entering the shoulder lane. The merging points of ramp vehicles were determined in watching each ramp vehicle traveling on an acceleration lane. Each site has a parallel-type acceleration lane and lengths of 3 sites are 150 meters for KwangJu, 400 meters for Hobub, and 350 meters for Seohanam interchanges.

As a result of the regression analysis with various functions, the following regression function was finally decided.

$$T_M = 4.9088 - 0.005678D - 0.000075868S_r^2 \qquad (27)$$

where

T_M : is critical gap (sec)

D : is the distance from the nose that a ramp vehicle enters in the shoulder lane (m)

S_r : is the speed of ramp vehicle at nose (km/h)

Equation (27) shows that the critical gap decreases as distance (D) and ramp vehicle's speed (Sr) increase and that the value of critical gap does not change sensitively as the speed of ramp vehicle increases when compared to distance variation. This means that the speed of ramp vehicle has little influence on the critical gap.

The signs of the estimated coefficients indicate how they contribute to the dependent variable. The coefficients of independent variables are expected to be negative because the critical gap is likely to decrease as the distance (D) or the speed of ramp vehicle (Sr) increase.

The critical value at a=0.05 with 2 degrees of freedom of numerator and 33 degrees of freedom of denominator, F(0.95;2,33), is 3.29. Since the calculated value of F ratio is 40.67 this regression function is significant. In addition, t statistic test is performed for showing that the coefficients of dependent variables are significant in the regression function developed. The result of ⟨Table 3⟩ shows that all coefficients are significant at significant level of 1% except for coefficient of Sr^2.

This equation can be used for calculating the critical gap in practical applications after D and S_r are substituted for S_D and L where S_r is an acceleration lane length and S_D is the design speed of ramp.

⟨Table 3⟩ Results of Statistical Test for Critical Gap Equation

Coeff.	Value	Std. error	t-stat.	P-value	R^2	F-stat.
Intercept	4.908857	0.166235	29.53	0.0000	0.7113	40.66677
D	-0.00568	0.000767	-7.41	0.0000		
Sr^2	-7.6E-05	2.95E-05	-2.57	0.0147		

⟨Table 4⟩ Critical Gap by the Length of Acceleration Lane (L_a) and Ramp Design Speed (S_D)

Acceleration Lane Length (m)		0	100	200	300	400	500
Ramp Design Speed	40 km/hr	4.906	4.338	3.770	3.202	2.635	2.067
	60 km/hr	4.904	4.336	3.769	3.201	2.633	2.065

⟨Table 4⟩ shows that the critical gap becomes smaller as the acceleration lane length increases and that the design speed of ramp has little influence on the critical gap.

Ⅵ. Conclusions

Over the decades, several studies have dealt with the traffic characteristics and phenomena at a merge area, however relatively few analytical techniques have been developed to evaluate the traffic flow at this area, especially ramp merge capacity.

This study focused on the merging behaviors that was characterized by the relationship between shoulder lane flow and on-ramp flow and modeled these behaviors to determine probabilistic ramp merge capacity by using gap acceptance theory. In the process of building the model, it was considered in this study that there were two types of ideal merge and forced merge when a ramp-merging vehicle entered the gap provided by the traffic flow of shoulder lane. It is common that the rampmerging vehicle sometimes enters into the gap that is smaller than the critical gap and this forced merge type was included in modeling ramp merge capacity.

The model for the critical gap was also proposed because the critical gap was the most influential factor to determine ramp merge capacity by developed models and the form of this model is composed of the length of acceleration lane and the design speed of ramp.

According to the developed model, it is shown that merge capacity value is on the increase as the critical gap decreases and the shoulder lane volume increases. Merge capacity also becomes smaller as the ramp volume increases; the higher the ramp volume, the lower merge capacity is. Furthermore, as the critical gap increases, merge capacity decreases very rapidly.

This study has two meanings: one is to model the merging behaviors including the forced merge type to determine merging capacity more precisely at a merge area and the other is to show that the merging capacity could vary with the different conditions of traffic flow.

The findings of this study would help analyze traffic phenomena and understand traffic behaviors at a merge area, and might be applicable to decide the primary parameters of on-ramp control by considering the effects of ramp merging flow.

Now that the developed models are greatly affected by the critical gap, it is noted that the incorrect use of critical gap causes to give the unreliable result of model. The complexity of developed equations would prevent from application widely in practical use.

In future studies, it is needed to evaluate the developed model using a lot of field data with various combinations of shoulder lane volume and on-ramp volume at a merge area site. In addition, due to the forced merge type the effects of ramp merging vehicles on the traffic flow of freeway should be studied more detailed.

References

1. Transportation Research Board (2000), "Highway Capacity Manual: Special Report 209", Washington D.C., USA.
2. Drew, D. R. et al. (1967) "Gap Acceptance in the Freeway Merging Process", Highway Research Record 208, TRB, pp.1~36.
3. Drew, D. R., Buhr, J. H., and Whitson, R.H. (1968) "Determination of Merging Capacity and Its Applications to Freeway Design and Control", Highway Research Record 244, TRB, pp.47~68.
4. Kim, S. G., Hatipkarasulu, Y., and Park, C. H. (2001), "A Ramp Merge Capacity Model Using Gap Acceptance Theory", Journal of EASTS, Vol.4, No.2, pp.101~112.
5. Kim, S. G. and Son, Y. T. (2003) "Development of A New Merge Capacity Model and the Effects of Ramp Flow on the Merge Capacity", CD Proceedings of the 82nd Transportation Research Board Annual Meeting, Washington, D.C., USA.
6. Elefteriadou, L, Roess, R. P., and McShane, W. R. (1995), "Probabilistic Nature of Breakdown at Freeway Merge Junctions", Transportation Research Record 1484, TRB, pp.80~89.
7. Lorenz, M. R. and Elefteriadou, L. (2001) "Defining Freeway Capacity as a Function of the Breakdown Probability", 7roceedings 80th TRB Annual Meeting, TRB, Washington, D.C., USA.
8. Kita, H. A. (1999) "Merging-Giveway Interaction Model of Cars in a merging Section: a Game Theoretic Analysis", Transportation Research Part A. 33, p.305~312.
9. May, A. D. (1990) "Traffic Flow Fundamentals", Prentice Hall, New Jersey.

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that will occur according to the route chosen.

This study tries to build a framework in which we can observe the learning behavior of the drivers' expectations of the travel time under nonstationary environment. In order to investigate how drivers have their subjective expectations on traffic conditions in response to public information, a numerical experiment is carried out.

We found that rational expectations(RE) formation about the route travel time can be expressed by the adaptive expectation model when the travel time changes in accordance with the nonstationary process which consists of permanent shock and transient shock. Also, we found that the adaptive parameter of the model converges to the fixed value corresponding to the route conditions.

Model Development Determining Probabilistic Ramp Merge Capacity Including Forced Merge Type

KIM, Sang Gu

Over the decades, a lot of studies have dealt with the traffic characteristics and phenomena at a merging area. However, relatively few analytical techniques have been developed to evaluate the traffic flow at the area and, especially, the ramp merging capacity has rarely been. This study focused on the merging behaviors that were characterized by the relationship between the shoulder lane flow and the on-ramp flow, and modeled these behaviors to determine ramp merge capacity by using gap acceptance theory. In the process of building the model, both an ideal mergence and a forced mergence were considered when ramp-merging vehicles entered the gap provided by the flow of the shoulder lane. In addition, the model for the critical gap was proposed because the critical gap was the most influential factor to determine merging capacity in the developed models. The developed models showed that the merging capacity value was on the increase as the critical gap decreased and the shoulder lane volume increased. This study has a meaning of modeling the merging behaviors including the forced merging type to determine ramp merging capacity more precisely. The findings of this study would help analyze traffic phenomena and understand traffic behaviors at a merging area, and might be applicable to decide the primary parameters of on-ramp control by considering the effects of ramp merging flow.

Estimation of Crosswalk Pedestrian Volume at Signalized Intersection

HA, Tae Jun · KIM, Jeong Hyun · PARK, Je Jin

Forecasting models for crosswalk pedestrian volume, which consider safety of crosswalks and good traffic operation accidents, have been established in order to reduce total number of crosswalk pedestrian accidents. However, the existing models did not include pedestrian volume which seemed to be very significant in the forecasting models because there were no pedestrian volume related data and no methods of estimating pedestrian volume. This paper presents estimating models for the total number of trips, which are produced in zone i and attracted to zone j, and a process of estimating pedestrian volume in the goal year.

First of all, the estimating models included the characteristics of land-use around a signalized intersection and the crosswalk pedestrian volume as factors. Secondly, the estimated crosswalk pedestrian volume was distributed to the crosswalk pedestrian volume each path in the basic year by friction factors of Gravity Model, adjustment factors for area and ratio of pedestrian volume who moved diagonally at the crosswalk. Thirdly, the estimating models of crosswalk pedestrian volume in the goal year were presented by using the distributed crosswalk pedestrian volume.