ON-RAMP MERGING CAPACITY IN JAPAN URBAN EXPRESSWAYS: A STOCHASTIC APPROACH

By Mohamed SHAWKY ** and Hideki NAKAMURA***

1. Introduction

Capacity of expressway facilities is traditionally treated as a constant value in traffic engineering guidelines around the world, such as Highway Capacity Manual (HCM2000)[1)]. The HCM defines the capacity as the maximum flow rate that can reasonably be expected to traverse a facility under prevailing roadway, traffic and control conditions. A constant value of capacity would mean that, given a capacity of 3,600 veh/h, the traffic should be fluent at a demand of 3,599 veh/h and be congested at a demand of 3,601 veh/h (Brilon et al. (2005)[2)]). This constant value concept may be convenient for geometric design purposes. However, for management and control purposes, it is not realistic where breakdown conditions occur over a wide range of flow rates. For example in ramp metering control systems, if the estimated capacity of the merging lane is 2000 veh/h and this value is used in the control algorithm while the breakdowns occur over a range 1900 to 2100 veh/h, clearly this system can not prevent from the breakdowns.

Hence, a new understanding of expressway capacity based on a stochastic approach has recently been introduced by some researchers (Elefteriadou et al. (1995) [3)], Persaud et al. (1998) [4)] and Lorenz and Elefteridou (2000) [5)]). In these researches the probabilistic nature of the breakdown phenomena has been affirmed as well as breakdown probability models were developed. They proved that the breakdown probability is an increasing function of mainline and ramp flow rates.

In Japan, Okamura et al. (2001)[6)] empirically investigated the breakdown probability at 19 bottlenecks on intercity expressways and proposed a stochastic procedure for estimating capacity by a cumulative percentile value of the probability. Recently, Oguchi (2004)[7)] investigated the breakdown probability at bottlenecks of expressway basic sections such as sag vertical curves. Also in this research, the breakdown probability was found to be an increasing function of mainline flow rates as well as the breakdowns occurred over a wide range of flow rates from 210 to 300 veh/5-min/2-lane. The majority of bottlenecks on Japan urban expressways are merging and/or weaving sections (Nakamura H. and Oguchi (2006)[8)]). The previous researches that had investigated the merging capacity of Japan expressways (Majid at al. (2001)[9)] and JSTE (2006)[10)]) treated its value from the traditional approach (i.e., as a constant value). They estimated the merging capacity as the capacity of the basic downstream segments of the merging sections during two flow regimes: congested and uncongested separately. However, the flow rates that trigger the breakdown phenomena at merging sections were not investigated through these researches.

This paper aims to investigate the randomness nature of the merging capacity in Japan urban expressways at three different traffic flow conditions: before breakdown, when breakdown occurs and after breakdown as well as to investigate the impacts of the geometric design such as acceleration lane length on the merging capacity at these flow conditions.

2. Data Collection

5-miunte detector data from April 2004 to March 2005 of Tokyo Metropolitan Expressway (MEX) and Nagoya Urban Expressway were used in this research. An initiative analysis was performed to identify the on-ramp merging sections where breakdowns frequently occur in these two expressway networks. Then, six merging sites with different acceleration lane length were selected; five of them are located on MEX and have a left on-ramp entrance, and one site is located on Nagoya Urban Expressway with a right on-ramp entrance. All of these sites are in 2-lane mainline sections. The general information of these sections is summarized in Table 1.

Table 1: Information of the selected merging sections

Section name	Location	On-ramp side	Acc. lane length (m)	Critical speed (km/h)	# of the observed breakdowns in 6 months
Shibakoen	Inner-ring, anticlockwise direction on MEX	left	70	53	357
Hakozaki	Route # 6, outbound direction on MEX	left	85	51	387
Daikancho	Inner-ring, anticlockwise direction on MEX	left	90	50	204
Iidabashi	Route # 5, outbound direction on MEX	left	100	58	162
Funaboribashi	Central-Ring, clockwise direction on MEX	left	180	60	149
Horita	Route # 3, inbound direction on Nagoya Exp.	right	150	60	185

* Keywords: on-ramp expressway, merging capacity, breakdown phenomenon
** Student Member of JSCE, M.Sc., Dept. of Civil Eng., Faculty of Eng., Nagoya University,
(Furo-cho, Chikusa-ku, 464-8603, Nagoya, Japan, TEL 052-789-5175, FAX 052-789-3837, shawky@genv.nagoya-u.ac.jp)
*** Member of JSCE, Dr.Eng., Dept. of Civil Eng., Faculty of Eng., Nagoya University,
(Furo-cho, Chikusa-ku, 464-8603, Nagoya, Japan, TEL 052-789-5175, FAX 052-789-3837, nakamura@genv.nagoya-u.ac.jp)

3. Breakdown Phenomena at Merging Sections

Data from three detectors around the merging sections are used to investigate the merging capacity and the breakdown events occur at merging sections. These three detectors are located in the upstream basic section (U), immediately downstream of acceleration lane (M) and downstream basic section (D). For example, Figure 1 shows the location of these detectors at Horita merging section of Nagoya Expressway.

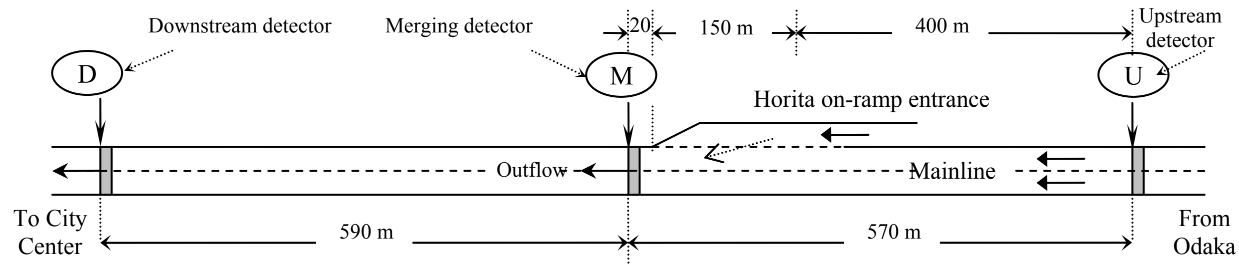


Figure 1: Detector locations and layout of Horita merging section

To eliminate the impact of the heavy vehicles on the data analyses, traffic volumes are converted into a passenger car unit per hour by using an equivalent factor of heavy vehicle equal to 1.7.

The breakdown phenomena at merging is here defined as "a reduction in speed at detector (M) to be under a critical value and this condition sustains flow at least 15 minutes while the speeds at (D) remain over this value". A typical example of this is shown in Figure 3. The critical speed (i.e., the threshold value between the congested and uncongested flow regimes) is estimated at each merging section from the fundamental relationship between speed and flow rate observed by detector (M) as shown in Figure 4. The estimated values of the critical speed and the observed number of breakdown events at all merging sections from data analysis over 6 months also listed in Table 1.

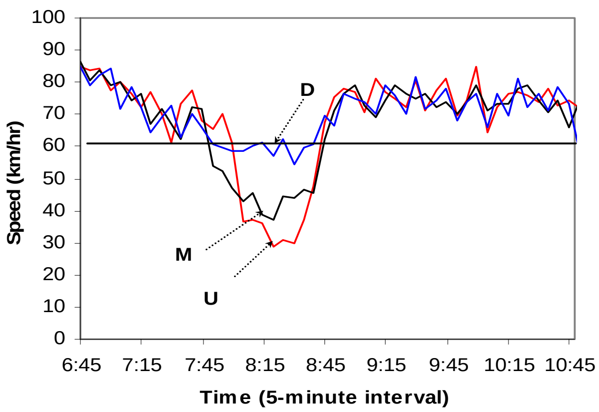


Figure 3: Example of a breakdown event occurred at Horita merging section in Sep. 8, 2004

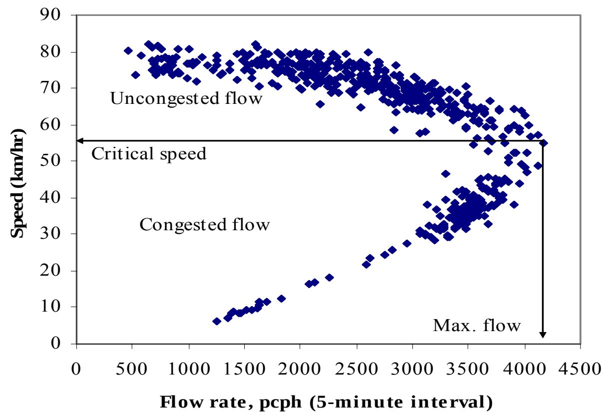


Figure 4: Example of speed-flow relationship observed by detector (M) at Iidabashi in Feb 5, 2005

4. Merging Capacity Investigation

Hereafter, the flow rates that were observed by detector (M) are called outflow rates. These outflow rates are here used to investigate the fluctuation of the merging capacity. Outflow and speed observations over time when breakdown events activated at each merging section are demonstrated. Figure 5 shows an example of these time series observations at Shibakoen section. From this figure three different outflow rate aspects are recognized: maximum flow rate before breakdown, flow rate when breakdown occurs (breakdown flow rate) and flow rates after breakdown (queue discharge flow rate). This figure shows two examples of breakdown: when breakdown occurs at the maximum flow rate (the morning breakdown event) and when breakdown occurs at flow rate lower the maximum flow rates (the evening breakdown event).

The values of the three aspects of outflow rates are extracted at all sections and then the histograms and cumulative distributions of them are demonstrated for the selected sections, as shown in Figure 6. It shows that the cumulative distribution of the breakdown flow falls between the distributions of the maximum and queue discharge flow rates. Various plausible function types such as the Normal, Logistic and Weibull distributions are tested to fit the distributions of the three outflow aspects. The least square technique is used to estimate the parameters of these functions. The Normal distribution was found to be the best representative of these flow aspects at all merging sections. Table 2 shows the means and standard deviations of the fit Normal distribution of these sections. It shows that the mean value of the breakdown flow always falls between the two mean values of the maximum and queue discharge flow rates. In addition, the mean values of the three outflow rates are significantly different among the investigated merging sections.

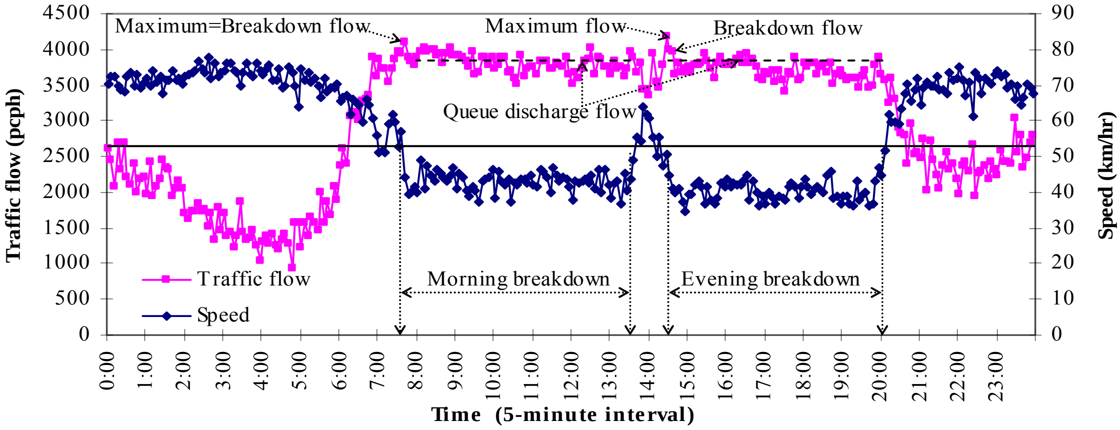
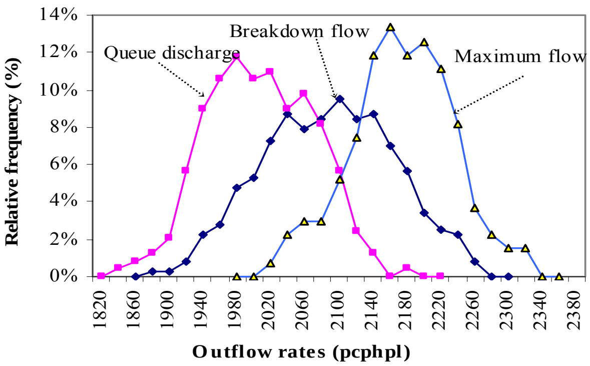
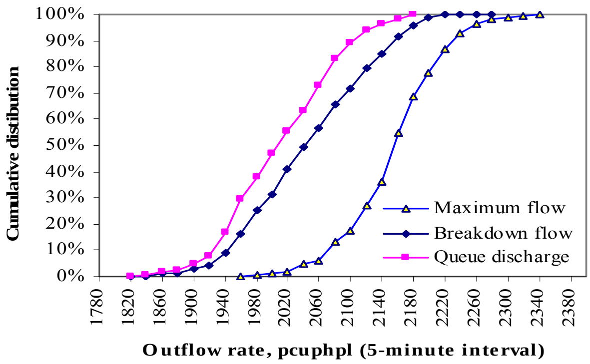


Figure 5: Two typical breakdown phenomena observed at Shibakoen merging section Jan. 28, 2005



a) The histogram of the different outflow rates



b) Cumulative distribution

Figure 6: Example of the observed distributions of the three outflow aspects at Horita merging section

Table 2 Normal distribution parameters of the tree aspects of flow rates

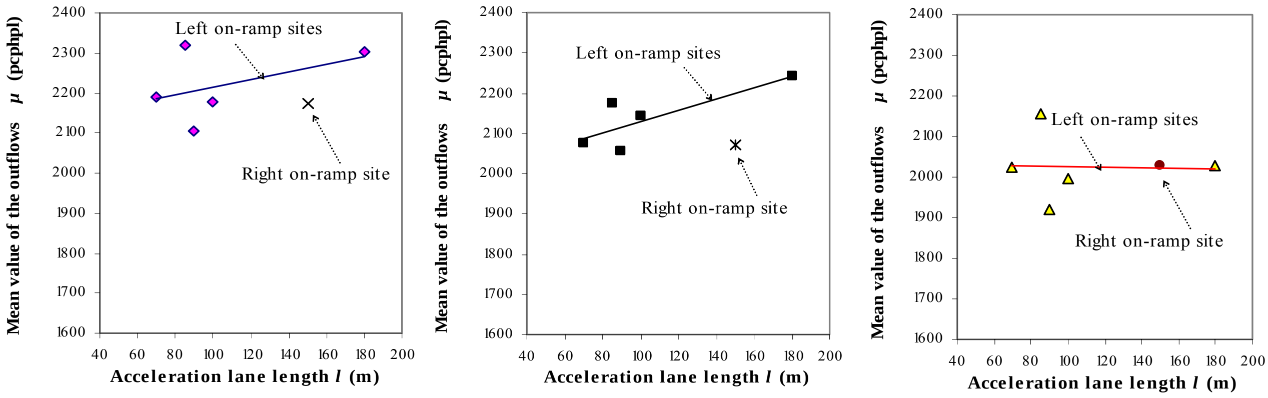
Merging section	Max. flow		Breakdown flow		Queue discharge flow		Capacity drop value (%)
	Mean (μ)	Std. Dev. (σ)	Mean (μ)	Std. Dev. (σ)	Mean (μ)	Std. Dev. (σ)	
Shibakoen	2189	57	2076	69	2025	82	7.5 %
Hakozaki	2318	99	2219	110	2155	108	7.0 %
Daikancho	2105	61	2054	81	1921	91	8.7 %
Iidabashi	2176	75	2141	79	1998	93	8.2 %
Funaboribashi	2304	113	2230	106	2029	90	11.9 %
Horita	2173	61	2070	80	2030	70	6.6 %

5. Impact of the Acceleration Lane Length on Merging Capacity

The relationships between the acceleration lane length l of left on-ramp merging sections and the mean values μ of the maximum, breakdown and queue discharge flow rates are shown in Figure 7 (a), (b) and (c), respectively. The linear regression in these figures shows the tendency of the μ values against l. Also the μ value of the right on-ramp merging site (Horita section) is demonstrated in the same figure to investigate the impact of the on-ramp side on the merging capacity of the three flow conditions. Figures 7 (a) and (b) show that the μ value of the maximum flow rates tends to increase with increasing l while this tendency is more significant in case of the breakdown flow rates than maximum flow rates. In addition, the μ value of the right on-ramp section is significantly small by comparing it with the estimated value of left on-ramp sections at the same value of l. Figure 7 (c) shows that no significant impact of l and ramp side on the μ value of queue discharge flow rates.

6. Capacity Drop Phenomenon

The capacity differences under the congested and uncongested traffic flow conditions is called "capacity drop phenomenon". Although this phenomenon has been investigated from more than a decade by Banks (1990)[11], there is no clear explanation for it. In this study, a capacity drop value is calculated as the relative difference between the mean values of the maximum and queue discharge flow rates. The calculated values of the capacity drop are also indicated in Table 2. It shows that the capacity drop value is not constant and ranges from 7 % to 11.9 %.



a) Maximum flow rates b) Breakdown flow rates c) Queue discharge flow rates

Figure 7: The relationship between l and μ of the different aspects of outflow rates

7. Conclusions

The presented stochastic approach of merging capacity in this study seems to be more realistic and useful than the traditional single value, especially for investigating the impacts of the geometric design on merging capacity. The observed significant difference of the mean values of the maximum and breakdown flow rates proved that the majority of the breakdown events occurred at flow rates lower than the maximum values. This revealed the weakness of the current definition of the merging capacity that depends on the maximum outflow rates. In addition, investigating the merging capacity under the three different traffic flow conditions explored how much the traffic condition affects the cumulative distribution of the merging capacity.

The geometric design in terms of the acceleration lane length and on-ramp side showed different impact levels on the merging capacity at the three flow conditions. The breakdown flow rates were more sensitive to these two geometric elements than the maximum flow rates. However, the queue discharge flow rates were not influenced by them at all. As a result, it seems the breakdown flow rate is more realistic to represent the merging capacity than other two flow rates.

Further research by using more merging sections and long period data are required to investigate more accurate relationships between the geometric design elements and merging capacity as well as to investigate the impact of other factors such as weather conditions and ramp flow ratio.

ACKNOWLEDGEMENT

Authors are grateful to Nagoya Expressway Public Corporation and Tokyo Metropolitan Expressway Company Ltd., for their cooperation in providing data necessary for this study.

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