THREE ASPECTS OF MERGING CAPACITY: THEIR STOCHASTIC NATURE

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The proper understanding of the fluctuation nature of merging capacity is essential for more effective management and control strategies of merging sections. This paper aims to analyze the stochastic nature of the merging capacity and breakdown phenomenon in Japan urban expressway on-ramp junctions as well as to investigate the impact of some factors on their distributions, such as geometric design and traffic flow characteristics. Cumulative distribution models of merging capacity are presented for three different traffic flow conditions: before breakdown, when breakdown occurs and after breakdown. In addition, two different breakdown probability models in terms of flow rate and occupancy measurements are provided. These distribution models are more realistic for ITS control applications of merging section than the single value concept of capacity that is currently used.

Keywords: *Merging capacity, Breakdown phenomenon, Ramp metering systems, Expressway on-ramp junction*

1. Introduction

Merging section is recognized as one of the most severe bottlenecks in urban expressway networks around the world. Therefore, this section has a long history with the control strategies started by ramp metering systems in 1961 [1] to the current trails of the automated control systems [2]. An accurate estimation of merging capacity value is an important requirement in these systems to perform its function. Capacity of merging sections is traditionally estimated as a constant value. A constant value would mean that, given a capacity of 3,600 veh/hr, the traffic should be fluent at a demand of 3,599 veh/hr and be congested at a demand of 3,601 veh/hr [3]. This constant value concept may be convenient for geometric design purposes. However, in management and control purposes, it is not realistic where recent studies proved that the merging capacity is not a constant value as well as the breakdown events occur over a wide range of flow rates [4-7]. In these studies, although this fluctuation nature was treated as a probabilistic phenomenon, the impacts of external factors such as geometric design and traffic characteristics on the merging capacity and breakdown probabilities have not investigated. Also, they have not discussed the possibilities of contributing the developed models to improve the existing applications of the Intelligent Transportation Systems (ITS).

By taking the ramp metering systems as an example of merging section control strategies, the existing control algorithms use a single critical value of flow rate or occupancy to identify the breakdown conditions and to provide the optimal ramp metering rates. These critical values are usually taken lower than the maximum observed capacity by a safety margin in order to cover its fluctuation nature [8]. As a result, these systems have successfully prevented the breakdown conditions but they failed to maximize the merging capacity. Hence, questions about the feasibility of these systems to increase the merging capacity or to sustain the observed maximum flow rate before breakdown have recently been raised by several researchers [9-11].

The discussion above concludes that understanding the stochastic nature of capacity and breakdown at merging is the core of any control systems. The main target of this paper therefore, is to analyze the merging capacity and the breakdown phenomenon in Japan urban expressway on-ramp junctions as well as to investigate the impacts of some factors that may affect their distributions such as geometric design in terms of acceleration lane length and ramp entrance side (right or left) and traffic flow characteristics in terms of on-ramp flow ratio. More than 2,600 breakdown events are observed and analyzed over one year in six merging sections located in 2-lane mainline segments.

Table 1 General information of the investigated merging sections

Section name	Location	On-ramp side	Acc. lane length (m)	Critical speed (km/h)	# of the observed breakdown events
Shibakoen	Inner-ring, anticlockwise direction on MEX	Left	70	53	753
Hakozaki	Route # 6, outbound direction on MEX	Left	85	52	744
Daikancho	Inner-ring, anticlockwise direction on MEX	Left	90	50	296
Iidabashi	Route # 5, outbound direction on MEX	Left	100	57	265
Funaboribashi	Central-Ring, clockwise direction on MEX	Left	180	60	230
Horita	Route # 3, inbound direction on Nagoya Exp.	Right	150	60	377

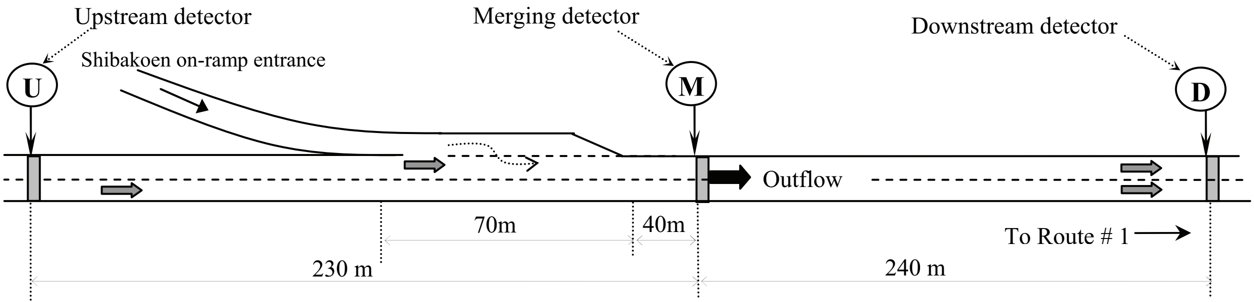


Figure 1. Detector location and layout of Shibakoen merging section (not to scale)

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 over these two expressway networks. Then, six merging sites located in two-lane segments with different acceleration lane length and on-ramp side 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. The general information of these sections is summarized in Table 1.

3. Breakdown Phenomenon Identification

Intensive existence of detector sites on Japan urban expressway networks (300-600m) enables us to detect the breakdown events that start in merging sections at the same 5-minute interval where there is always a detector located just downstream of the merging area. Data from three detectors around the merging sections are used to identify the breakdown events that occurred from the investigated sites. These detectors are located in the upstream basic section (U), immediately downstream of acceleration lane (M) and downstream basic section (D) as shown in Figure 1 (example of Shibakoen section).

The breakdown event is here defined as "a reduction in speed at detector (M) to be lower than a critical value and this condition sustains for at least 15 minutes while the downstream speeds at (D) remain over this critical value". A typical example of a breakdown event occurred at Iidabashi section is shown in Figure 2. The critical speeds are estimated by identifying threshold values between the congested and uncongested flow in the fundamental flow-speed relationships observed by detector (M). The mean values of the estimated critical speeds and the observed number of breakdown events at the investigated merging sections from data analysis over a whole year are also listed in Table 1.

4. Merging Capacity Investigation

4.1. Stochastic nature of merging capacity

Hereafter, the flow rates that were observed by detector (M) are called outflow rates. The impact of heavy vehicle on the estimation process of merging traffic values by converting the analyzed traffic values into a passenger car unit per hour. An equivalent factor of 1.5 for a heavy vehicle is used in this research [12].

Outflow rate and speed observations are figured over time when the observed breakdown events activated. Figure 3 shows a typical example of these figures. From the figure, three different aspects of outflow rates (i.e. merging capacity) are identified:

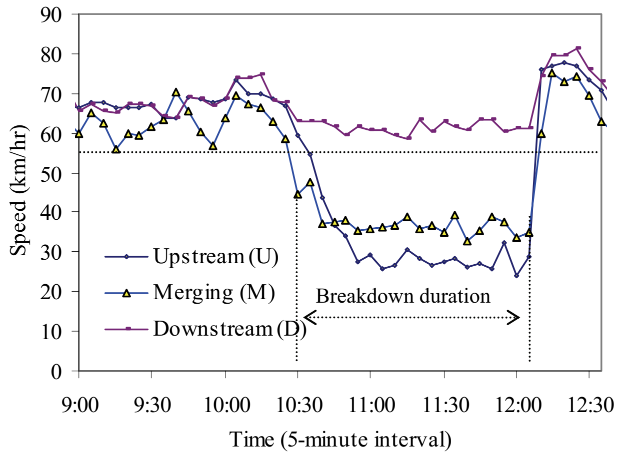


Figure 2. Speed profile of the three detectors at Iidabashi merging section

maximum outflow before breakdown, outflow rate when breakdown occurs and outflow rate during the breakdown period (queue discharge flow).

Other than this example, sometimes two exceptional cases can also be observed. The first case takes place when the breakdown occurs at once with the maximum pre-breakdown outflow rate. In this case, the breakdown flow and maximum flow rates are the same value. The second case occurs when the maximum outflow rate is observed during the breakdown period. In this case, the maximum pre-breakdown flow is skipped and the observed maximum value is incorporated into the queue discharge analysis.

The values of the three aspects of merging capacity are extracted from the breakdown events of all sections. These values are classified into intervals of 20 pcphpl. Then, the cumulative distributions of them are demonstrated as shown in Figure 4. It shows that the distribution of breakdown flow always falls between the distributions of the maximum pre-breakdown and queue discharge flow rates. However, the relative position of the breakdown flow distributions to the positions of the other two distributions varies. Some cases are near the maximum pre-breakdown distribution, and the others are near the queue discharge distribution.

A worthy point of discussion here is the extent of the shift of the breakdown distribution to the left in relation to the maximum pre-breakdown distribution. This shift in the distribution is considered as the breakdown capacity drop phenomenon. Two factors affect the shift value; the number of breakdown events occurred at flow rate lower than the maximum pre-breakdown flow rate and the value of the breakdown capacity drop of each breakdown event. By increasing the number of breakdown events that occurred at outflow rate lower than the observed maximum pre-breakdown flow, the shift value increases. Also, the shift value increases by increasing the breakdown capacity drop of the individual breakdown events. In other words, if all the breakdown events occurred at the maximum outflow rates, the breakdown and maximum pre-breakdown flows rate distributions are identical.

Moreover, Figure 4 shows that the queue discharge flow rates are always lower than maximum pre-breakdown flow rates. The difference between them is usually called in literatures [13, 14] as the capacity drop phenomenon. However, in order to distinguish this phenomenon from the breakdown capacity drop phenomenon mentioned above, it will here be called queue discharge capacity drop phenomenon. No clear explanation of this phenomenon exists in literatures, Where as Brilon, et al. [3] discussed hypotheses on its reasons. These reasons are mostly turned to driver behavior and vehicle acceleration abilities.

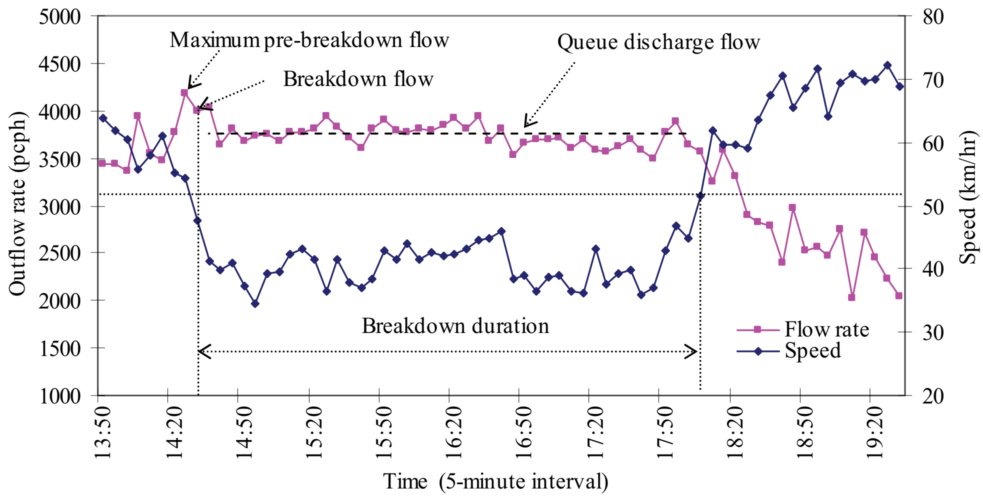
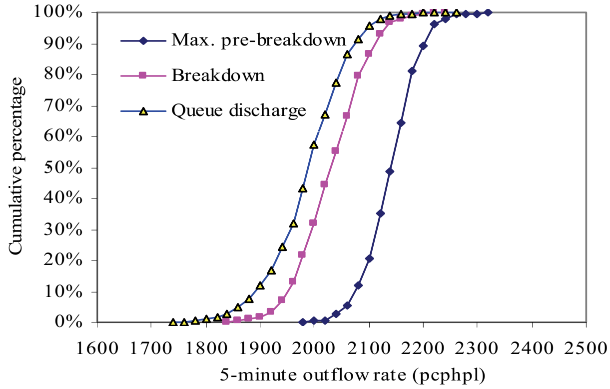
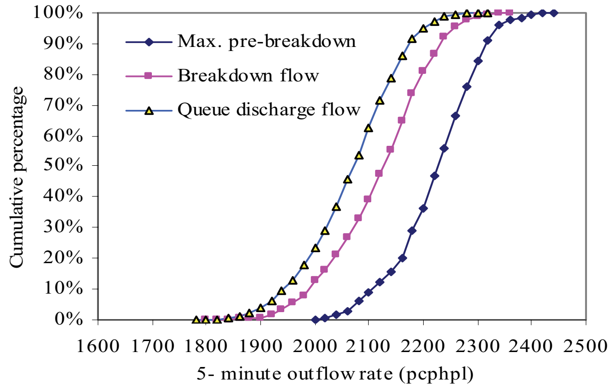


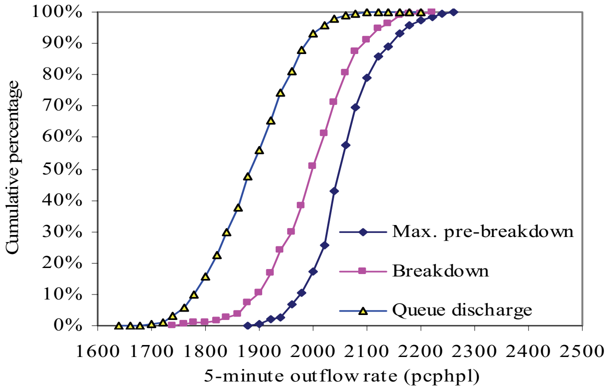
Figure 3. Example of a breakdown event observed at Shibakoen section on Jan. 28, 2005



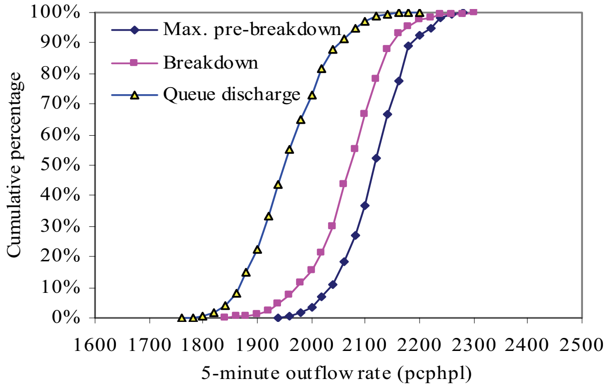
a) Shibakoen section



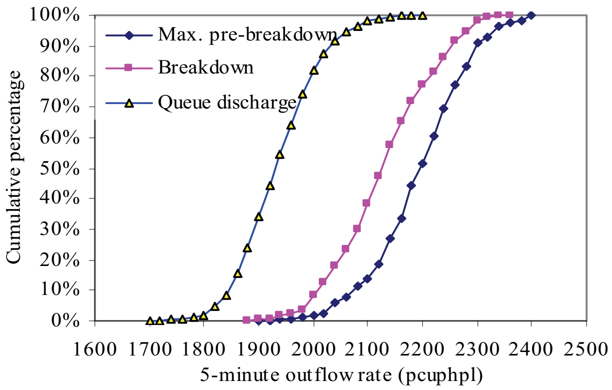
b) Hakozaki section



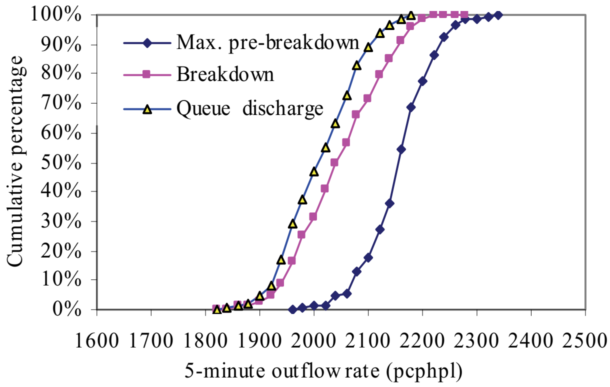
c) Daikancho section



d) Iidabashi section



e) Funaboribashi section



f) Horita section

Figure 4. Observed distributions of the three aspects of merging capacity at the investigated sections

Table 2. Examples of the statistical test results at Hakozaki and Horita sections

Section Name	Merging capacity distribution type	# of Observations	Min.	Max.	R^2	Chi^2	*P*-value
Hakozaki	Max. pre-breakdown	283	1,998	2,420	0.996	7.151	0.0281
	Breakdown	744	1,821	2,364	0.990	12.44	0.0022
	Queue discharge	5,513	1,809	2,325	0.999	9.853	0.0000
Horita	Max. pre-breakdown	192	1,953	2,356	0.992	4.614	0.0498
	Breakdown	463	1,821	2,205	0.994	37.89	0.0000
	Queue discharge	1,252	1,821	2,155	0.999	5.962	0.0500

Table 3. The Normal distribution parameters of the three aspects of merging capacity

Section name	Max. pre-breakdown flow		Breakdown flow		Queue discharge flow		Breakdown capacity drop	Queue discharge capacity drop
	Mean (a)	Std. Dev.	Mean (b)	Std. Dev.	Mean (c)	Std. Dev.	$\frac{(a)-(b)}{(a)}$	$\frac{(a)-(c)}{(a)}$
Shibakoen	2,159	50	2,050	62	1,962	64	5.0%	9.1%
Hakozaki	2,241	78	2,135	116	2,084	85	4.7%	7.0%
Daikancho	2,108	79	2,017	78	1,905	79	4.3%	9.6%
Iidabashi	2,149	62	2,081	134	1,975	71	3.2%	8.1%
Funaboribashi	2,212	88	2,147	90	1,954	73	2.9%	11.7%
Horita	2,128	58	2,037	88	1,992	69	4.3%	6.4%

4.2. Merging capacity modeling

To identify the differences among the observed distributions of merging capacity aspects over the investigated sections, these distributions have to be modeled. Skewness-Kurtosis test for normality are used to verify the fitness of these distributions to the Normal distribution. Table 2 summarizes the results of the statistical tests for Hakozaki (left entrance) and Horita (right entrance) as examples. Since the results show that the *p*-values are not greater than 0.05, the Normal distribution is concluded as a good representative for the observed distributions at a significant level of 5%.

Table 3 shows the mean and standard deviation values of the fit Normal distribution functions at all sections. It shows that the standard deviations for the maximum pre-breakdown and queue discharge flow rates over the different sections are relatively smaller than those of the breakdown flow rate.

The differences among capacity distributions are examined by using t-test of distribution comparison as shown in Table 4. Since the all t-values between each pair of distributions are greater than the critical t-value at 5% significant level of 1.96, it concludes that the means of the capacity distributions are different at 5% significant level. Also, the same test is used to compare the capacity distributions of the same aspect over sections. It was found that the capacity distribution aspects are also different over sections at a significant level of 5%.

Table 4. Comparison between capacity distributions

Section name	t-value between the capacity dist. of		
	Max. and breakdown	Max. and queue dis.	Break. and queue dis.
Shibakoen	25.028	58.145	35.172
Hakozaki	18.012	32.557	14.875
Daikancho	8.018	26.267	23.95
Iidabashi	7.951	29.063	24.361
Funaboribashi	7.035	34.908	30.377
Horita	7.577	22.963	16.118

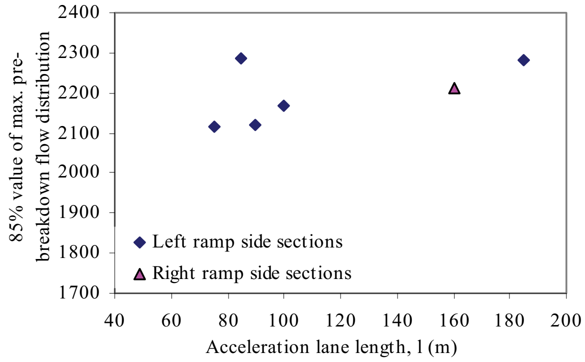
The values of the two aspects of capacity drop phenomena are calculated based on the mean values of The three aspects of merging capacity as listed in Table 3. It shows that the values of the two capacity drop phenomena are not constant. The breakdown capacity drop ranges from 2.9 % to 5.0% with an average of 4.1% and the queue discharge capacity drop ranges from 6.4 % to 11.7 % with an average of 8.3%.

5. Geometric Design Impact on Merging Capacity

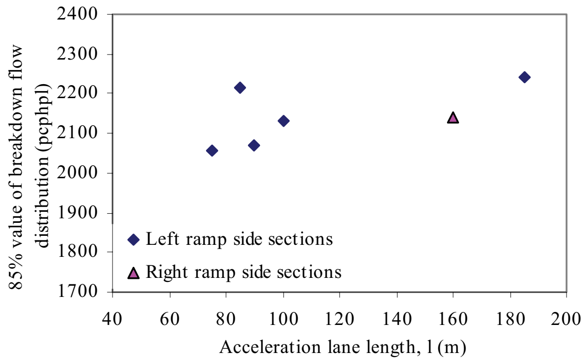
The impacts of the geometric design on the three aspects of merging capacity distributions are investigated in terms of acceleration lane length l and on-ramp entrance side (left or right). The 85 percentile value is usually used to represent the cumulative distribution of field observations of random variable. Therefore, this value is here used to distinguish the differences among the observed distributions. Figures 5(a), (b) and (c) show the relationship between the 85 percentile values of merging capacity distribution at each section versus section length l. These figures show that the merging capacity tends to increase with increasing l for two aspects of merging capacity; the maximum pre-breakdown flow and breakdown flow while the merging capacity after breakdown (queue discharge flow rates) is not influenced by l. However, the number of the data sample in Figure 5 is limited and it should be increased to define accurate relationships between l and capacity distributions.

6. Ramp Flow Impact on Merging Capacity

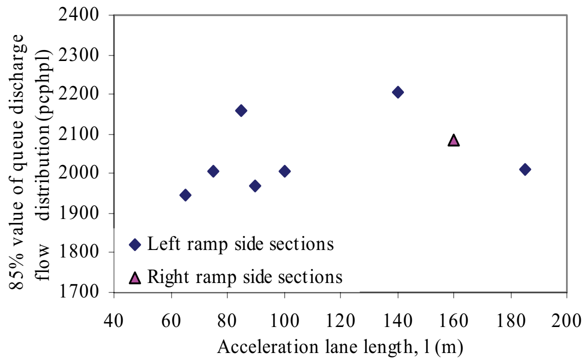
Although it can be considered that the ramp flow rate may influence the fluctuation of merging capacity, this has not yet been investigated in any existing studies. In this chapter, this impact is examined in Shibakoen section due to its relatively high number of breakdown observations and due to the observed wide range ramp flow rates. The share of the on- ramp traffic



a) Maximum pre-breakdown flow rate

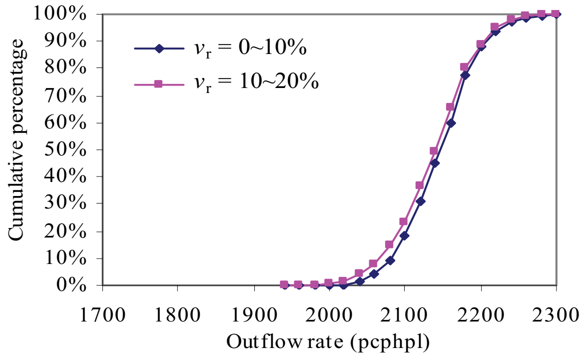


b) Breakdown flow rate

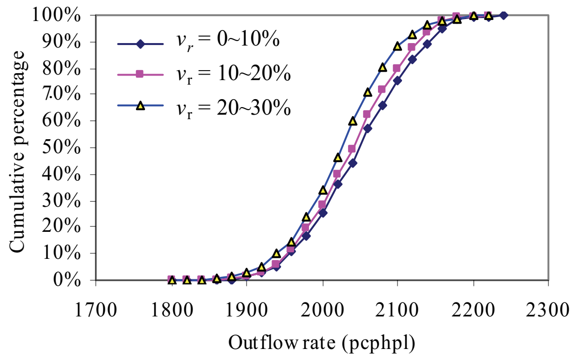


c) Queue discharge flow rate

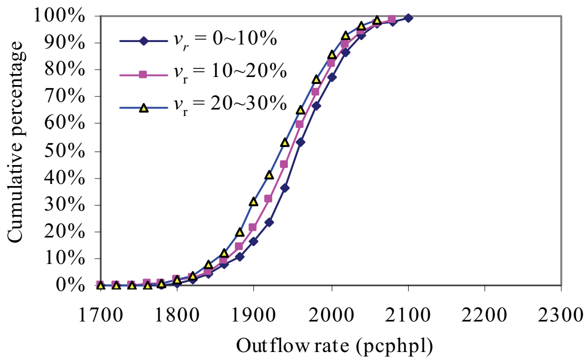
Figure 5. The relationship between l and the 85 percentile value of merging capacity distributions



a) Maximum pre-breakdown flow rate



b) Breakdown flow rate



c) Queue discharge flow rate

Figure 6. Cumulative distributions of merging capacity aspects by ramp flow ratio

Table 5. The Normal distribution parameters of merging capacity at different levels of ramp flow ratio

Merging capacity aspect	Ramp flow ratio, v_r	# of observations	Min.	Max.	Mean value	Std. dev.	Chi^2	*P*-value
Max. pre-breakdown	0~10%	128	1,980	2,179	2,155	50.3	16.63	0.0000
	10~20%	141	1,951	2,173	2,147	51.4	24.68	0.0000
Breakdown	0~10%	147	1,902	2,216	2,057	59.8	8.524	0.0769
	10~20%	467	1,875	2,252	2,050	62.5	6.331	0.0847
	20~30%	139	1,872	2,205	2,040	63.9	18.14	0.0934
Queue discharge	0~10%	161	1,794	2,106	1,967	64.1	21.49	0.0468
	10~20%	1,209	1,765	2,254	1,955	62.6	14.47	0.0009
	20~30%	516	1,775	2,153	1,945	63.1	12.75	0.0246

tvolumes, ramp flow ratio v_r, in the three aspects of merging capacity are calculated as a relative percentage of on-ramp flow rates to outflow rates that observed at the same time interval. The observed ranges of v_r are 2.9~24.0%, 1.3~30.1% and 4.0%~35.5% for the maximum pre-breakdown, breakdown and queue discharge flows, respectively.

The values of the merging capacities are classified based on the v_r value into classes of 10% interval. The cumulative distributions of each merging capacity aspect at different levels of v_r are demonstrated in Figures 6 a), b) and c). They show that the merging capacity distributions are influenced by the ramp flow ratio v_r, especially for the breakdown and queue discharge capacities. The t-test also shows that these distributions are difference at significant level of 5%.

In order to illustrate these impacts, the relationship between the 85 percentiles of the observed distributions versus v_r is demonstrated in Figure 7. It shows that these aspects of merging capacity decrease with increasing v_r. The statistical tests of normality concluded that the Normal distribution fits these distributions well at the 5% level of significance, and fits the breakdown flow at the 10% level of significance as shown in Table 5. It shows that the standard deviation values are almost constant for each capacity aspect while the mean values decrease with increasing v_r for the three aspects of merging capacity.

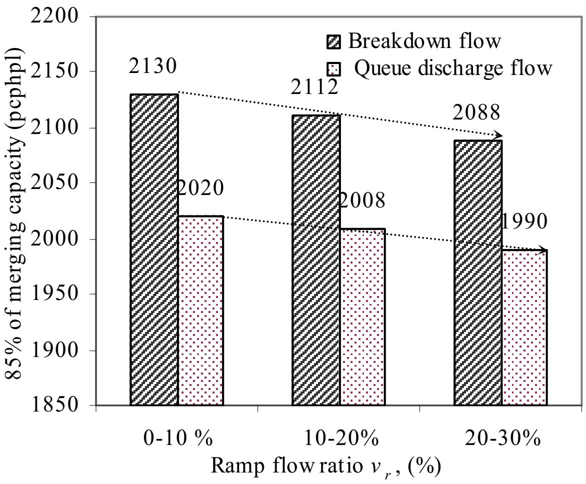


Figure 7. The 85 percentile values of merging capacity distribution at different levels of v_r.

7. Breakdown Probability Investigation

7.1. Breakdown probability estimation

From the discussion above a question about the probability of the breakdown at a given value of the breakdown at a given value of outflow rate has been raised. A previous research [15] presented breakdown probability models at the same investigated merging sections from data analysis over 6 months. It shows that the breakdown probability is an increasing function of outflow rate. In this paper, the breakdown probability is investigated by using a whole year data.

The breakdown probability values are calculated by comparing the number of breakdown events that occurred at a given value of outflow rate with the total number of observation at the same outflow rate. Several theoretical functions such as Weibull, Logistic and Normal distributions are tested to fit the observed breakdown probabilities. The Maximum Likelihood method is used to choose the best representative function of breakdown probability. It is found that the Weibull function is the best one since it gives the highest value of the Log-likelihood at all sections as shown in Table 6. The Weibull function is:

$$F(x) = 1 - e^{-\left(\frac{x}{\beta}\right)^{\alpha}} \tag{1}$$

Where,

x : outflow rate (pcphpl)

α : shape parameter

β : scale parameter

The estimated values of these parameters and the statistical test results are summarized in Table 7.

Figure 8 shows the observed and estimated breakdown probabilities at all sections. It shows that the shape of the distributions does not significantly change while their locations vary over the different sections.

Table 6. The log-likelihood values of the three tested distribution functions

Section name	Weibull	Logistic	Normal
Shibakoen	-22.241	-39.281	-40.984
Daikancho	-31.061	-42.729	-50.102
Hakozaki	-30.466	-38.226	-49.158
Iidabashi	-25.935	-27.119	-38.527
Funaboribashi	-32.403	-42.963	-45.321
Horita	-30.262	-45.258	-52.187

7.2. Geometric design impact on the breakdown probability

Unlike the 85% representative value of the cumulative distributions of direct field observations, any value of the calculated breakdown probability distributions can be used to distinguish the differences among them. The outflow rate at 50% value of breakdown probability P_{50} is here used where the probability of breakdown and non-breakdown is equal.

Table 7. Estimated values of the Weibull distribution parameters of the observed breakdown probability

Section name	α	β	Log-likelihood	P-value	Chi^2	R^2
Shibakoen	28.6	2,138	-22.2411	0.00	73.45	0.949
Hakozaki	28.7	2,256	-30.4657	0.00	135.3	0.921
Daikancho	28.5	2,139	-31.0611	0.00	177.2	0.956
Iidabashi	27.8	2,162	-25.9346	0.00	111.7	0.958
Funaboribashi	27.5	2,317	-32.4029	0.00	163.6	0.948
Horita	26.7	2,142	-30.2618	0.00	129.7	0.927

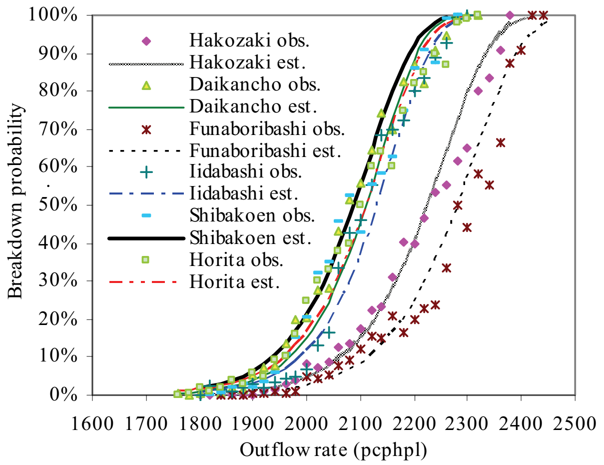


Figure 8. Observed and estimated values of the breakdown probability over the investigated sections

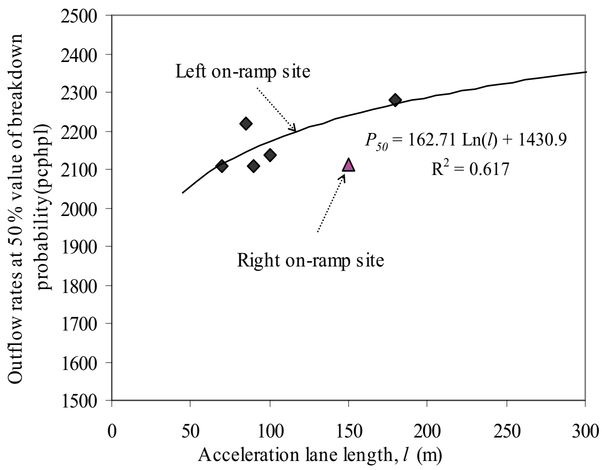


Figure 9. The relationship between P_{50} and the acceleration lane length l

The values of P_{50} versus the acceleration lane length l of all sections are demonstrated as shown in Figure 9. The linear regression is not appropriate for modeling this relationship due to the fact of the upper limit of merging capacity. As a result, the logarithmic function is here used. In the left ramp side cases, it shows that P_{50} value increases with increasing l which means the breakdown probability value decreases by increasing l at the same outflow rate. Also, the P_{50} value of the right on-ramp side section is demonstrated in the same figure to show the impact of the on-ramp side on the breakdown probability. It shows that the breakdown probability of the right on-ramp section is significantly high by comparing with the left on-ramp side at the same value of l and outflow rate. A reasonable justification of this finding is that in the left traffic system like in Japan the right lane usually have a higher traffic demand and speed than the left lane, especially when the traffic volume approaches the capacity. That means the merging capacity may be improved by redistributing the traffic demand over the mainline lanes.

7.3. Occupancy based breakdown probability

In this section, a new breakdown model based on the occupancy measurements of detector (M) is

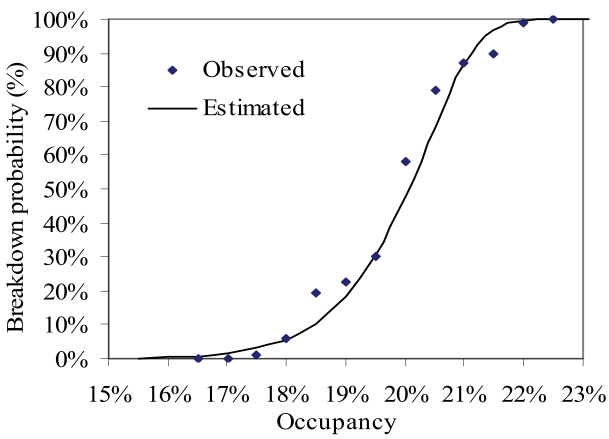


Figure 10. The breakdown probability values as a function of occupancy at Iidabashi site

presented. The occupancy observations simultaneously cover the impact of all vehicle types in terms of vehicle length. The observed occupancy value when the breakdown occurs is here called breakdown occupancy O_b. The analysis shows that the breakdown events occurred over a relatively small range of O_b values from 18 to 23% at all sites. This reveals that the occupancy measurements may be more suitable to follow the breakdown phenomenon than the traffic flow rate.

The breakdown and non-breakdown events are classified based on the occupancy observations into classes of 0.5% interval. Then the breakdown probability is calculated by comparing the number of the breakdown events that occurred at a given value of occupancy with the total observations at the same occupancy value. Figure 10 shows the observed values and estimated Weibull distribution of the breakdown probability at Iidabashi section as an example.

8. Discussion on ITS Applications

The accurate estimation of merging capacity is the core of any ITS applications at merging sections. This chapter discusses the feasibility of using this study's findings to improve the efficiency of such ITS applications as the ramp metering and driver behavior control systems. Figure 7 proves that each of the mainline and ramp flow rates affects the merging capacity. This means the merging capacity can be improved by controlling each of them separately or by controlling both of them in an integrated control system.

Ramp control system is a widely used strategy for avoiding breakdown conditions at merging sections by controlling ramp flow rate. As mentioned before in the introduction, the existing ramp metering systems apply a single critical value of capacity lower than the maximum observed value, e.g. 90% of maximum capacity, in order to cover its fluctuation nature which loses 10% of merging capacity. To overcome this drawback, these systems should apply a stochastic model of capacity or breakdown probability like shown in Figures 5, 6 and 8 in stead of this single value concept. For example, the ramp metering rate can be calculated in order to maintain the breakdown probability at merging section under an acceptable value. However, determining this acceptable value should be carefully examined. In addition, a comparison study between the single and stochastic concepts of merging capacity should be conducted for validating this approach.

On the other hand, the discussion of Figure 9 in section 7.2 implies the possibility of increasing the merging capacity through controlling the mainline lane utilization ratio and/or speed of vehicles over lanes. By encouraging the upstream drivers who run on the merging lane to change their lane, the merging capacity may increase. Lane changing behavior and speed profiles may be controlled through variable message signs (VMS), in-vehicle information systems and intelligent speed adaptation (ISA). The efficiency of applying such systems to improve the merging capacity needs to be examined in the real world.

9. Conclusions

The purposes of this paper were to investigate the stochastic nature of merging capacity and breakdown phenomenon in Japan urban on-ramp junctions as well as to explore the impacts of geometric design and ramp flow rates on their distributions. Three aspects of merging capacity were investigated; maximum pre-breakdown, breakdown and queue discharge. The following conclusions were extracted from this research:

- The presented distribution models of the three aspects of merging capacity seem to be more realistic and more useful than the traditional single value concept of capacity.
- The significant differences among the distribution functions of the three aspects of merging capacity proved that the majority of breakdown event occurred at flow rates lower than the maximum pre-breakdown flow rate.
- A new capacity drop phenomenon called breakdown capacity drop was investigated based on the differences between the maximum pre-breakdown and breakdown flow distributions.
- Ramp flow ratio significantly affects the merging capacity in its three aspects, especially during the breakdown formation.
- The geometric design in terms of acceleration lane length and ramp side significantly affects the capacity. By increasing the acceleration lane length l, the pre-breakdown and breakdown capacities increase. However, the merging capacity after breakdown is not influenced by them.
- These geometric items also have impacts on the breakdown probability. By increasing l, the breakdown probability decreases. In addition, right ramp entrance gives a high value of breakdown probability under the same outflow rate and acceleration lane length.
- The occupancy measurements seem to more useful for tracking the breakdown conditions than the traffic flow rate.
- Three possible alternatives of ITS applications at merging sections were discussed in the light of this study's findings.

10. Recommendations

Through this research, several questions have been raised about the reasons of the stochastic nature of the three aspects of merging capacity as well as the reasons of the two observed capacity drop phenomena. To find answers for these questions further studies are recommended. Since we can presume that driver behavior is a major reason of these phenomena, an additional research should be conducted to investigate its impacts on the merging capacity. Further research in applying the provided distributions of merging capacity and breakdown probability for control purposes is recommended as well.

Acknowledgments

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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- *Received date: August 25, 2006*
- *Received in revised form: Feb. 13, May 8, and May 17, 2007*
- *Accepted: May 23, 2007*
- *Editor: Eiichi Taniguchi*