# A STUDY ON MERGING CAPACITY FLUCTUATION ON JAPAN URBAN EXPRESSWAYS


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# ABSTRACT

This paper aims to investigate the stochastic nature of merging capacity by using data from Japan urban expressways as well as to examine the impacts of some external factors on capacity distribution, such as section geometry and traffic flow characteristics. Traffic flow rates when breakdowns occur are analyzed at eight on-ramp sections over one year where more than 3,100 breakdown events have been observed. Three possible definitions of merging capacity are discussed; maximum pre-breakdown, breakdown and queue discharge flow rate. These three aspects of capacity are shown as random variables and they follow the Normal distribution function.

## 1. INTRODUCTION

On-ramp merging section is recognized as a severe bottleneck on many urban expressway networks all over the world. Merging capacity is traditionally estimated as a single constant value in all traffic engineering guidelines around the world, such as the US Highway Capacity Manual (HCM-2000) and German HBS 2001. This constant value would mean that, given a capacity of e.g. 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 (Brilon et al., 2005). However, doubts about the constant value concept of capacity were raised by Elefteriadou et al. (1995) who proved the probabilistic nature of the traffic breakdown, i.e., transition from an uncongested state to a congested state, at two freeway sections downstream of on-ramps. Thereafter, a number of researchers have investigated the breakdown probability at different types of freeway bottlenecks; such as weaving sections (Minderhoud et al., 1997), merging sections (Persaud et al. (1998); Jodie et al. (2001); Lorenz et al. (2001); Shawky and Nakamura (2006; 2007)), basic sections (Okamura et al. (2000, 2001 and 2006); Oguchi (2004)), and lane drop section (Brilon et al., 2005). All of these researchers proved the probabilistic nature of the breakdown phenomenon at the same section and it is an increasing function of traffic flow rate. However, they only estimated the capacity value when the breakdowns start to occur (i.e., breakdown capacity). On the other hand, the stochastic nature of capacity by using comprehensive estimation concepts has recently been investigated by several researchers. The findings of these researchers are summarized in the following paragraphs.

Abishai and Moshe (2002) investigated the stochastic nature of freeway capacity at three weaving section bottlenecks. In this study, the capacity was estimated from the speed-flow relationship as the intersection point of two linear regression models of the congested and uncongested data. Their analyses showed that the shifted gamma distribution function fits well the observed capacity distribution. They concluded that the 5th percentile values of capacity distribution could be adopted as the representative design values of capacity. Another conclusion is that the average distribution of capacity is relatively close to the distribution of capacities in the middle lane.

Elefteriadou et al. (2003; 2006) discussed three definitions of capacity; maximum pre-breakdown, breakdown and maximum queue discharge flow rates (QDFs). In these studies, the maximum observed single value of flow rate within the queue discharge period was taken as a representative of the queue discharge capacity. They analyzed 5− and 15-minute data for 80 breakdown events at two merging sections. The breakdown conditions were recognized when average speed drops below 70 km/hr at one section and

80 km/hr at the other one. Their analyses showed that the capacity distributions follow the Normal distribution function as well as the breakdowns occurred at flow rate less than both the maximum pre-breakdown and QDFs.

The most recent comprehensive analysis that treated the capacity as a random variable have been done with German motorway data by Brilon et al. (2005; 2006; 2007). In these studies, the traffic breakdown was defined as a reduction of average speed within one 5-minute interval from a high level to below a threshold of 70km/hr. They estimated the capacity as the extreme point of the fitted one regime parabolic curve of the flow-speed relationships observed downstream of two bottleneck sections; lane drop and basic. They concluded that the stochastic concept of capacity seems more realistic and more useful than the traditional use of constant-value capacities. In addition, the Weibull distribution function was provided as the best representative of the observed capacity distributions.

The discussion above implies that there is no common methodology to estimate the capacity of a given roadway facility such as merging sections, and the existing definition of single-value concept does not capture the real stochastic observations of capacity. Accordingly, this paper aims at investigating the stochastic nature of the capacity at on-ramp merging sections by using data collected from Japan urban expressways. In addition, it examines the impacts of some external factors on the capacity distribution, such as acceleration lane length, ramp-side entrance, and ramp flow ratio.

## 2. DATA COLLECTION AND CASE STUDIES

5-minute detector data from April 2004 to March 2005 of Tokyo Metropolitan Expressway (MEX) and Nagoya Urban Expressway were used in this study. An initiative analysis was performed to identify the active merging section bottlenecks over these two expressway networks. The queue formation is identified when the speeds drop to be lower than a critical value which was identified as a speed threshold between the congested and uncongested flow regimes. This critical value was estimated through extensive analyses on flow-speed relationships of detector data in subject expressway sections throughout a whole year. Figures 1 (a) and (b) show two examples of flow-speed relationships observed immediately downstream of Horita and Shibakoen on-ramp sections where the critical speed is estimated as 60 and 53 km/hr, respectively.

The dense allocation of detector sites (double-sensor overhead detectors with around 300m spacing) over Japan urban expressway networks enabled us to figure the speed drop duration along the expressway routes as shown in Figure 2 (an example of Inner-ring route on MEX). Since the shaded areas in this figure identify the queues (speed drop) location, duration, and length, the bottleneck positions are defined. Then, eight active bottlenecks at on-ramp merging sections with different acceleration lane length and on-ramp side (right or left entrance) are selected; seven 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. Note that all of the selected sections are in tangent 2-lane mainline segments and they have one-lane on-ramp with parallel acceleration lane type. The general information of the selected sections and their estimated critical speed values are summarized in Table 1.

## 3. BREAKDOWN PHENOMENON AT MERGING SECTIONS

The term "breakdown" of flow is generally used to describe the transition from uncongested to congested flow regime. Data from three detectors around the merging sections are here used to identify the breakdown events that started from the merging sections. 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 3 (an example of Horita section). The close positions of detector (M) from the end of the acceleration lane enable us to detect the breakdown event at the same interval of time when the speed drop is observed.

Accordingly, the breakdown phenomenon is 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". In this definition, the speed drop duration is restricted to be longer than 15 minutes in order to assure the formation of queues upstream of the merging section due to the breakdown event. A typical example of a breakdown event occurred at Horita merging section is shown in Figure 4. In this figure, the speed drop observed at detector (U) also made us confirm the formation of traffic queues due to the traffic breakdown. The number of the detected breakdown events over one year at each merging section is also listed in Table 1.

## 4. MERGING CAPACITY FLUCTUATION ANALYSIS

### 4.1. Identifying Three Aspects of Merging Capacity

The merging capacity values are estimated from the outflow rate observed by detector (M) at the all sections. The impact of heavy vehicle on the estimation process of merging capacity is eliminated by converting the analyzed traffic volumes into a passenger car unit per hour. An equivalent factor of 1.5 for a heavy vehicle is used in this study (Majid et al., 2001).

Time-series figures of outflow rate and speed observations are demonstrated when the detected breakdown events are activated. Figures 5 (a), (b), and (c) show typical examples of these figures observed at Horita section for three different cases of breakdown events; (1) when a breakdown occurred at once with the observed maximum outflow rate, (2) when a breakdown occurred at flow rate lower than the observed maximum pre-breakdown outflow rate, and (3) when the maximum outflow rate observed within the QDFs duration, respectively. The percentage share of observed breakdown events for case (1), (2) and (3) is 33.5%, 56.8% and 9.7%, respectively.

From Figure 5, three different aspects of outflow rates (or merging capacity) are recognized: maximum pre-breakdown, breakdown and QDFs. The maximum pre-breakdown capacity takes place when the maximum outflow rate is observed before starting the breakdown conditions. The breakdown capacity is defined as the outflow rate at the interval of time when the breakdown event starts to occur. The queue discharge capacity is defined as the outflow rates after starting the breakdown conditions when the queues are formed upstream of merging (congested flow at detector (U)) while the downstream flow is fluent (uncongested flow at detector (D)). Since the QDFs are not constant during the queue discharge period of each breakdown event, all of the 5-minute observations of the QDFs are used as individual samples in the analyses. In case (3), the maximum pre-breakdown flow is not observed before breakdown and the observed maximum value after breakdown is incorporated into the queue discharge analysis.

Based on the definitions above, the values of the three aspects of merging capacity are extracted from each observed breakdown event. Then, these values are classified into intervals of 20 pcphpl, and the cumulative distributions of them are demonstrated at the all sections as shown in Figures 6 (a)~(h). They show that the breakdown flow distribution always falls between the distributions of the maximum pre-breakdown and QDFs. Note that the observed breakdown flow rate of each individual breakdown event does not necessarily occur between the maximum pre-breakdown and queue discharge flow rate of this event as shown in Figure 5. Accordingly, in Figure 6, the relative position of the breakdown flow distributions to the positions of the other two distributions varies (sometimes near the maximum pre-breakdown distribution or near the QDFs distribution). The observed three aspects of merging capacity shown in Figure 6 make us confirm two previous findings in literatures; 1) the capacity-drop phenomenon, and 2) the phenomenon that the traffic breakdown does not necessarily occur as a result of the maximum flow rate.

In Figure 6, a worthy point of discussion is the extent of the shift of the breakdown distribution to the left in relation to the maximum pre-breakdown distribution. This shift is the product of the accumulative of the difference value between the maximum pre-breakdown and breakdown flow rates that is observed at each breakdown event of case (2) in Figure 5. That means the shift size between the maximum pre-breakdown and breakdown distributions increases with increasing the difference between the maximum pre-breakdown and breakdown flow rates of individual breakdown events. Also, it increases with increasing the percentage share of breakdown events in case (2) to the total number of observed breakdown events. In other words, if the all breakdown events occur simultaneously at the maximum pre-breakdown flows, the maximum pre-breakdown and breakdown flow distributions should be identical (i.e., the shift size equal zero). From this discussion, a question about the reasons of this shift has been raised.

Elefteriadou (1995) observed that immediately before breakdown, large ramp-vehicle clusters entered the freeway stream and disrupted traffic operations. Also, Cassidy and Rudjanakanoknad (2002) reported an important finding showed that a few minutes before the breakdown; a strong negative correlation occurred between the magnitudes of the on-ramp flow and the outflow rates. These two findings may support our assumption of that the random arrival of ramp vehicles and driver behavior during merging process are the main reasons of the three observed cases of breakdown phenomenon. If the ramp vehicles arrive in short headway times, a series of speed reductions of mainline vehicles occurs for gap opening processes in order to let ramp vehicles to merge safely. In addition, large gaps are created when a slow or heavy ramp-vehicle enters the mainline stream. These opened gap sizes may be greater than the desired following gap sizes at the same mainline speed level when vehicles run through the merging section without merging events. To verify these assumptions, the authors are currently analyzing the interrelationships among some microscopic measurements when the breakdowns occur.

### 4.2. Merging Capacity Modeling

To distinguish the differences among the observed distributions of the merging capacity aspects over the investigated sections, these distributions are modeled. Skewness-Kurtosis test for the normality is used to verify the fitness of the observed capacity distributions to the Normal distribution function. The results of this statistical test are summarized in Table 2. Since the *p*-values are not greater than 0.1, the Normal distribution is turned out to be a good representative for the observed capacity distributions at a significant level of 10%. Table 2 also shows that no significant differences in the standard deviation values among the three aspects of capacity at the same section. However, the standard deviation values vary over the different sections for the same aspect of capacity. In addition, the mean values are significantly different for the capacity aspects over the investigated sections. Figure 7 shows an example of the observed and fitted probability distribution of the three aspects of merging capacity at Horita section.

## 5. RAMP GEOMETRY IMPACT

As mentioned before in Section 2, the geometric design differences in the investigated sections are the acceleration lane length and ramp-side entrance. Therefore, the differences among the distributions of the same merging capacity aspect over sections are referred to these two geometric elements. The $85^{th}$ percentile values of the observed merging capacity distributions are extracted at all sections. Then, the relationships between these values and section length $l$ is demonstrated for the maximum pre-breakdown, breakdown and queue discharge capacities as shown in Figures 8 (a), (b) and (c), respectively. They 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 queue discharge capacities are not influenced by $l$. Note that, this tendency is more sensitive in case of breakdown capacity than the maximum pre-breakdown capacity.

In order to develop a model for the relationships shown in Figure 8, the number of the investigated sections should be increased. However, it is expected that the increasing tendency of capacity in terms of $l$ is not linear due to the fact of the upper limit of capacity. Although the number of data samples are limited, we can recognize two groups of data points in Figures 8 (a) and (b) surrounded by dashed lines. In the left-side data set, the increasing of capacity value against $l$ is steep, while the right one shows insignificant influences.

The $85^{th}$ percentile value of the capacity of the right-side ramp section is also demonstrated in Figure 8 to investigate the impact of the ramp-side on the merging capacity. It shows that the right-side on-ramp section has a significantly low value of pre-breakdown and breakdown capacities at the same value of $l$ while the queue discharge capacity is not influenced by the ramp-side.

## 6. RAMP FLOW RATE IMPACT

The impacts of on-ramp flow rate on the three aspects of merging capacity are investigated in Shibakoen section because of its relatively high number of the observed breakdown events and the observed wide range of on-ramp flow rates. The share of the on-ramp traffic volumes in the merging capacity (ramp flow ratio $v_r$) during the three aspects of outflow rate is 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 QDFs, respectively.

The maximum pre-breakdown, breakdown and QDFs capacities are classified based on the $v_r$ value into classes of 10% interval, and their cumulative distributions are demonstrated at each interval as shown in Figures 9 (a), (b) and (c), respectively. These figures show that the distributions of the three aspects of merging capacity are significantly influenced by the ramp flow ratio $v_r$. However, the impact of $v_r$ is more significant in case of breakdown and QDFs than the maximum pre-breakdown flow rate. The Normal distribution function also fits well these distributions at significance level of 10% as shown in Table 3. It shows that the standard deviation values are relatively close at the same aspect of capacity while the mean values decrease with increasing $v_r$.

To illustrate the impacts of the ramp flow rate on the merging capacity, the relationship between the 85 percentiles of the observed distributions versus the ramp flow ratio $v_r$ is demonstrated in Figure 10 for two aspects of merging capacity; breakdown and QDFs. It shows that these aspects of merging capacity decrease with increasing the ramp flow ratio.

## 7. CAPACITY DROP PHENOMENA

The capacity-drop phenomenon is defined in literatures as a reduction of the maximum flow rates when queues form. This phenomenon was firstly investigated by Banks (1990) from detector data and videotapes that were installed immediately downstream of freeway bottlenecks. Thereafter, several researchers (e.g., Hall et al., (1991); Cassidy et al (1999); Bertini et al (2002); Brilon et al., (2005)) proved the existence of this phenomenon at different freeway bottlenecks. A wide rage of the capacity drop values from 2% to 11% can be found in these studies.

In this paper, the existence of this phenomenon has been confirmed also on Japan urban expressway merging sections as shown in Figure 6 where the observed QDFs distributions are always lower than maximum pre-breakdown flow distributions at the all sections. The observed values of the capacity-drop phenomena over the investigated sections are listed in Table 4. These are average values of the difference between the maximum pre-breakdown and queue discharge capacity values. It shows that the capacity drop values range from 5.7% to 11.7% with an average of 7.8 %.

## 8. CONCLUSIONS

The purposes of this paper were to investigate the stochastic nature of merging capacity in Japan urban on-ramp sections as well as to investigate the impacts of the geometric design and ramp flow rates on the merging capacity distributions. The merging capacity was investigated as a random value during three different traffic flow conditions: maximum pre-breakdown, when breakdown occurs and after breakdown. These three aspects of merging capacity seemed to be stochastic phenomena and they should be estimated in a probabilistic manner. The following conclusions are extracted from this study:

- The existing single-value definition of merging capacity does not capture its stochastic nature. The distribution concept of merging capacity seemed to be more realistic and more useful than the traditional single-value concept for investigating the impacts of external factors on the merging capacity.
- The Normal distribution function fitted well the observed distributions of the three aspects of merging capacity with different mean values over different sites and merging capacity aspects.
- The significant differences among the distribution functions of the merging capacities proved that the majority of breakdown events occurred at flow rates less than the maximum pre-breakdown flow rate.
- The geometric design in terms of acceleration lane length and ramp entrance side significantly affected two aspects of merging capacity: maximum pre-breakdown and breakdown while the queue discharge flow rates were not influenced by them.
- Existence of the capacity-drop phenomena on the investigated sections had been confirmed and its values at all sections are presented.
- Ramp flow ratio significantly affected the three aspects of merging capacity, especially the breakdown capacity. Since the merging capacity aspects have been

influenced by the mainline and ramp flow rates, each or both of them should be controlled in order to alleviate the breakdown conditions.

## 9. RECOMMENDATIONS

In this paper, all analyses were conducted by using 5-minute data due to the limitation of data availability. For more accurate investigations of the three aspects of merging capacity distributions, a further research is recommended by using lane data in a finer time interval. On the other hand, several questions were raised through this paper about the reasons of the stochastic nature of the three aspects of merging capacity. To find answers for these questions further researches are recommended.


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**Table 1 General information of the investigated merging sections**

| No. | Section name | Location | Ramp side | Acc. lane length (m) | Average critical speed (km/hr) | observed no. of breakdown events |
|---|---|---|---|---|---|---|
| 1 | Gaien | Route # 4, outbound direction on MEX | Left | 65 | 60 | 170 |
| 2 | Shibakoen | Inner-ring, anticlockwise direction on MEX | Left | 75 | 53 | 753 |
| 3 | Hakozaki | Route # 6, outbound direction on MEX | Left | 85 | 52 | 744 |
| 4 | Daikancho | Inner-ring, anticlockwise direction on MEX | Left | 90 | 50 | 296 |
| 5 | Iidabashi | Route # 5, outbound direction on MEX | Left | 100 | 57 | 265 |
| 6 | Kandabashi | Inner-ring, anticlockwise direction on MEX | Left | 140 | 54 | 362 |
| 7 | Funaboribashi | Central-Ring, clockwise direction on MEX | Left | 180 | 60 | 230 |
| 8 | Horita | Route # 3, inbound direction on Nagoya Exp. | Right | 160 | 60 | 377 |

**Table 2 The Normal distribution parameters of the three aspects of merging capacity**

| Section Name | Merging capacity distribution type | # of Observations | Min. | Max. | Mean | Std. Dev. | *P*-value |
|---|---|---|---|---|---|---|---|
| Gaien | Max. pre-breakdown | 60 | 1,952 | 2,161 | 2,023 | 46 | 0.0477 |
| | Breakdown | 170 | 1,854 | 2,140 | 1,968 | 54 | 0.0624 |
| | Queue discharge | 334 | 1,740 | 2,052 | 1,880 | 64 | 0.0042 |
| Shibakoen | Max. pre-breakdown | 263 | 2,007 | 2,324 | 2,159 | 50 | 0.0604 |
| | Breakdown | 693 | 1,872 | 2,252 | 2,050 | 62 | 0.08366 |
| | Queue discharge | 1,864 | 1,765 | 2,254 | 2,006 | 71 | 0.0038 |
| Hakozaki | Max. pre-breakdown | 283 | 1,998 | 2,420 | 2,241 | 78 | 0.0281 |
| | Breakdown | 744 | 1,821 | 2,364 | 2,137 | 92 | 0.0022 |
| | Queue discharge | 5,513 | 1,809 | 2,325 | 2,084 | 88 | 0.0000 |
| Daikancho | Max. pre-breakdown | 144 | 1,916 | 2,365 | 2,108 | 79 | 0.0000 |
| | Breakdown | 296 | 1,772 | 2,232 | 2,017 | 78 | 0.0879 |
| | Queue discharge | 4,024 | 1,677 | 2,148 | 1,905 | 79 | 0.0000 |
| Iidabashi | Max. pre-breakdown | 131 | 1,980 | 2,291 | 2,149 | 62 | 0.0915 |
| | Breakdown | 266 | 1,863 | 2,303 | 2,088 | 69 | 0.0940 |
| | Queue discharge | 1,395 | 1,793 | 2,207 | 1,975 | 71 | 0.0000 |
| Kandabahi | Max. pre-breakdown | 171 | 2,115 | 2,480 | 2,271 | 71 | 0.037 1 |
| | Breakdown | 362 | 1,992 | 2,372 | 2,184 | 75 | 0.049 3 |
| | Queue discharge | 1,224 | 1,947 | 2,358 | 2,142 | 75 | 0.041 4 |
| Funaborib-ashi | Max. pre-breakdown | 156 | 1,956 | 2,422 | 2,212 | 88 | 0.0439 |
| | Breakdown | 230 | 1,851 | 2,337 | 2,147 | 90 | 0.0624 |
| | Queue discharge | 1,158 | 1,743 | 2,184 | 1,954 | 73 | 0.0042 |
| Horita | Max. pre-breakdown | 192 | 1,953 | 2,356 | 2,128 | 58 | 0.0498 |
| | Breakdown | 463 | 1,821 | 2,205 | 2,037 | 88 | 0.0000 |
| | Queue discharge | 1,252 | 1,821 | 2,155 | 1,992 | 69 | 0.0500 |

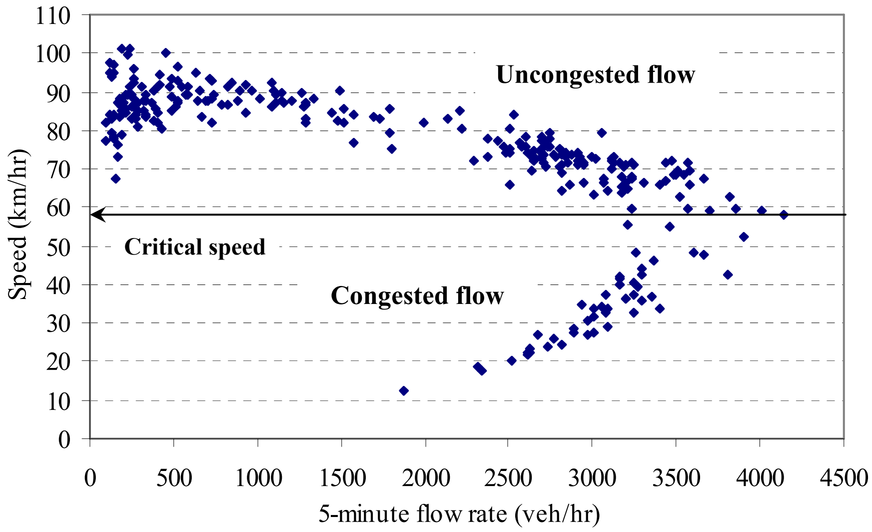
**Table 3 Statistical results of The Normal distribution for merging capacity at different levels of ramp flow ratio**

| Merging capacity aspect | Ramp flow ratio, $v_r$ | Number of observations | Min. | Max. | Mean | 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 | 2.756 | 0.0246 |

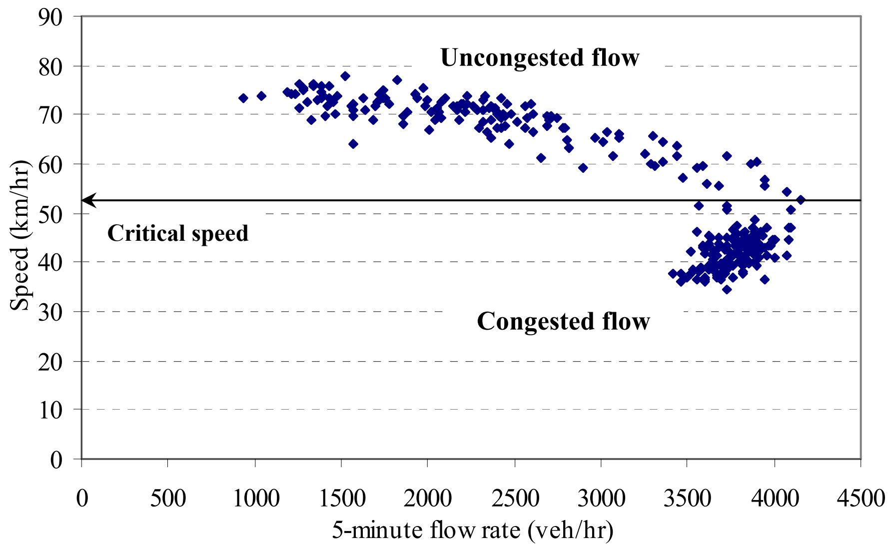
**Table 4 The observed values of the capacity-drop**

| Section name | Capacity-drop value |
|---|---|
| Gaien | 6.8% |
| Shibakoen | 7.1% |
| Hakozaki | 7.0% |
| Daikancho | 9.6% |
| Iidabashi | 8.1% |
| Kandabahi | 5.7% |
| Funaboribashi | 11.7% |
| Horita | 6.4% |

## List of Figures




(a) Horita on-ramp merging section (Dec. 15, 2004)




(b) Shibakoen on-ramp merging section (Jan. 28, 2005)

**Figure 1 Examples of flow-speed relationships observed immediately downstream of two merging sections**

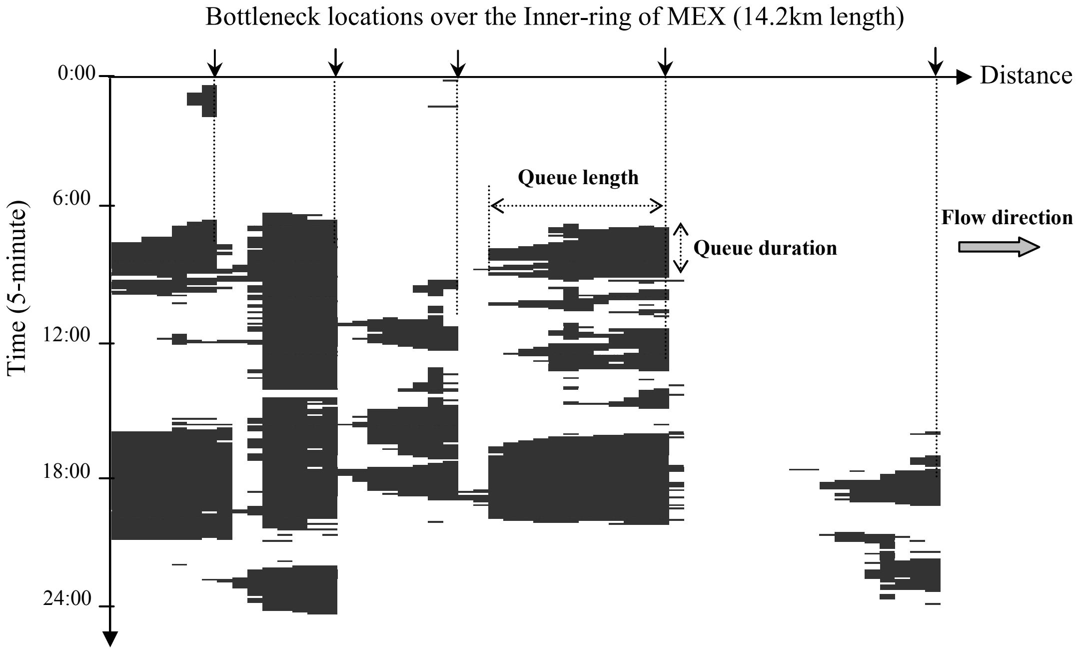



**Figure 2 Identifying the location of bottlenecks over the Inner-ring of MEX (Jan. 22, 2005)**

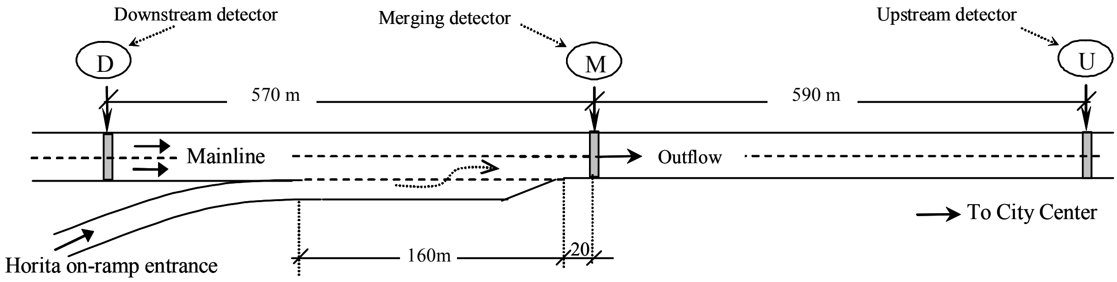



**Figure 3 Detector location and layout of Horita on-ramp merging section (not to scale)**

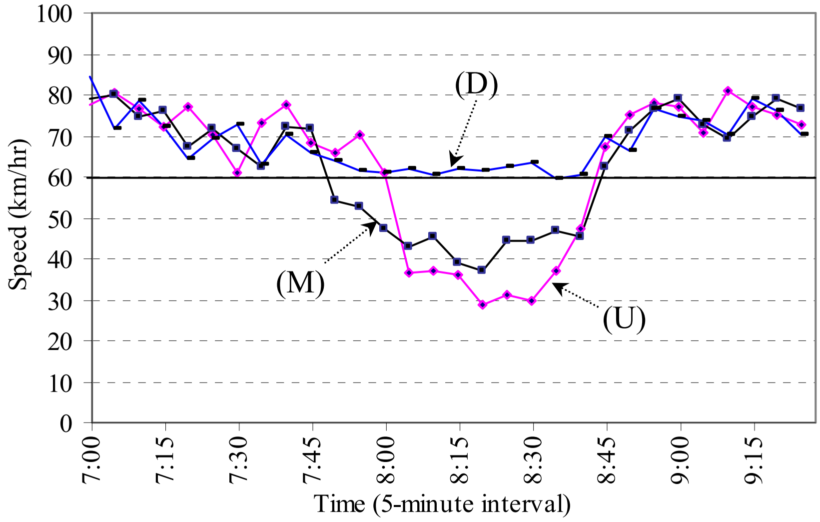
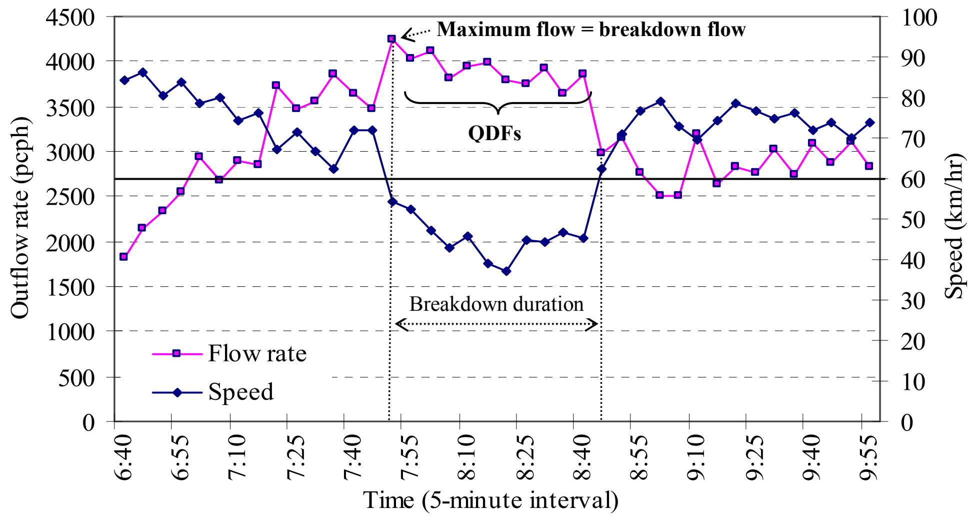
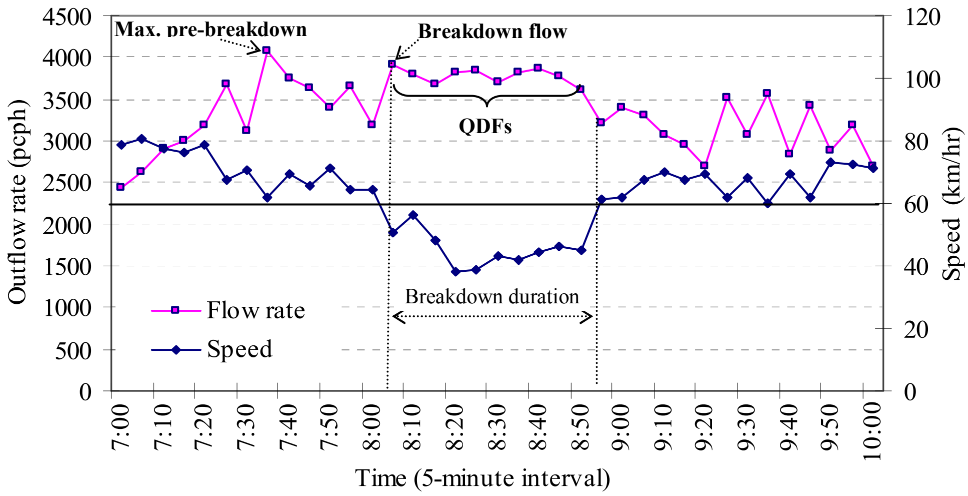


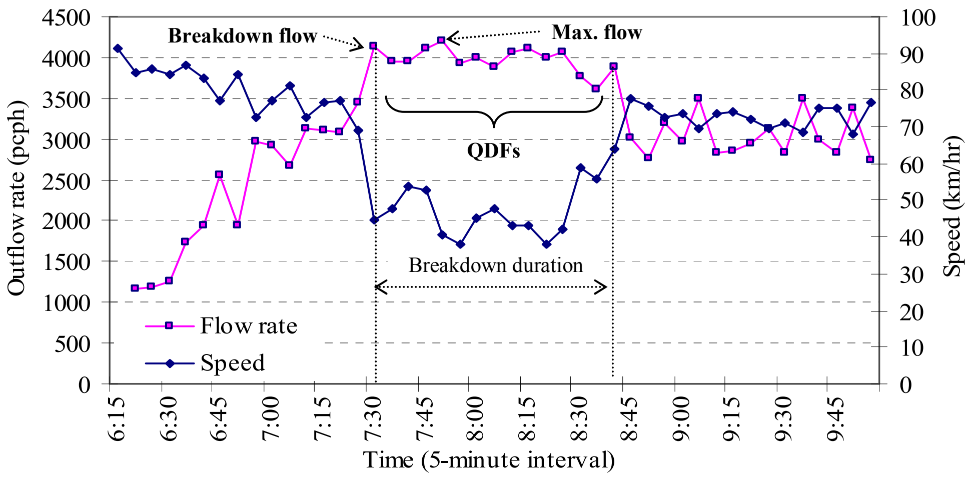

**Figure 4 Speed profiles at the three subject detectors of Horita merging section**




(a) Breakdown event observed on Dec. 20, 2004, Case (1)




(b) Breakdown event observed on March 18, 2005, Case (2)




c) Breakdown event observed on Dec. 16, 2004, Case (3)

**Figure 5 Typical examples of breakdown events observed at Horita section by detector (M)**

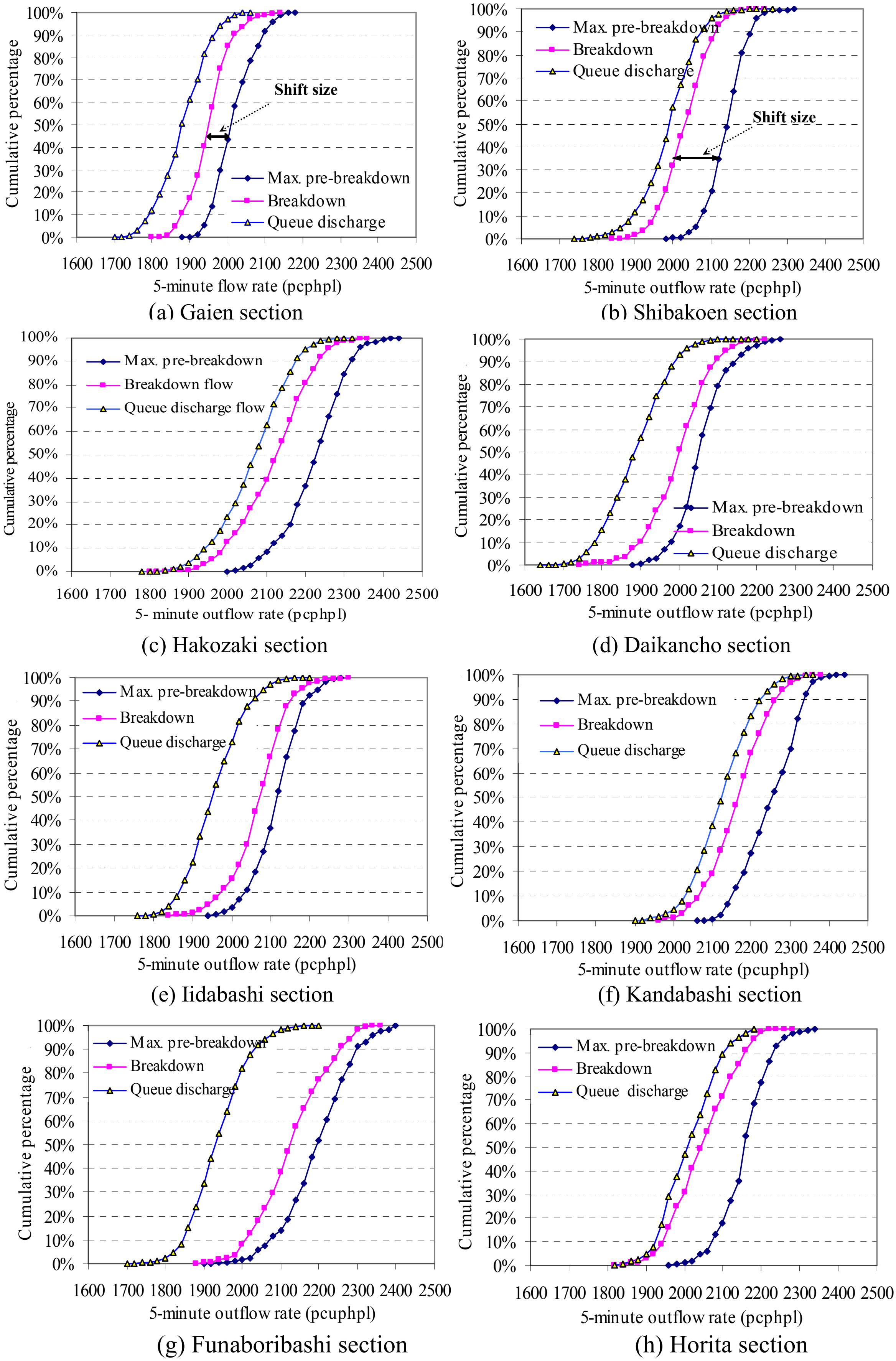



**Figure 6 Observed distributions of the three aspects of merging capacity at all sections**

Shawky and Nakamura, 2007, p. 25

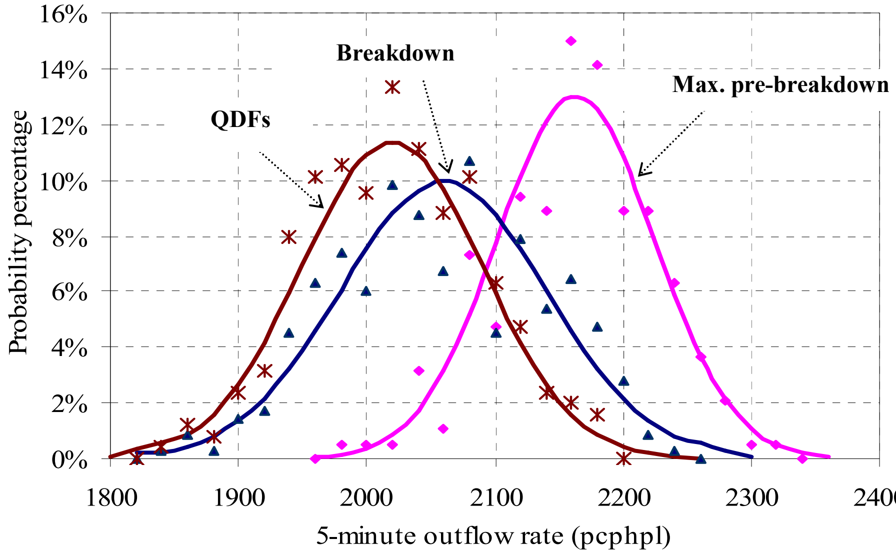
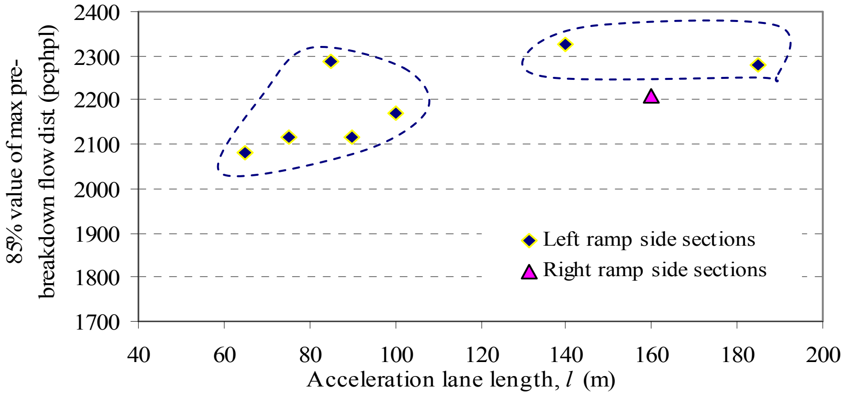
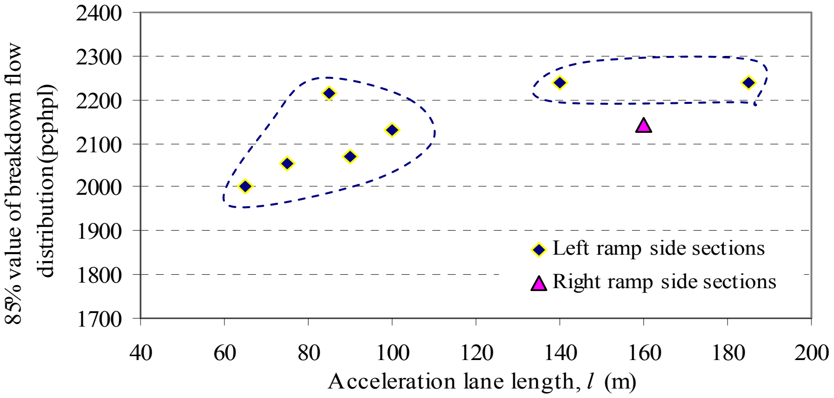


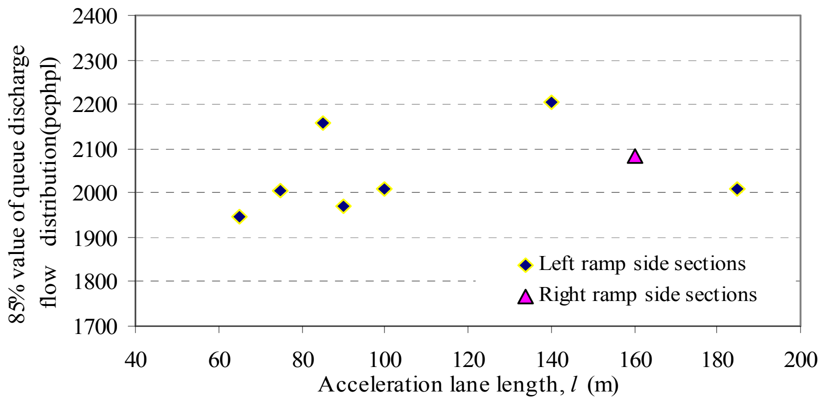

**Figure 7 The observed and the fitted Normal distributions of the probability distributions of merging capacity aspects at Horita section**




(a) Maximum pre-breakdown capacity versus *l*

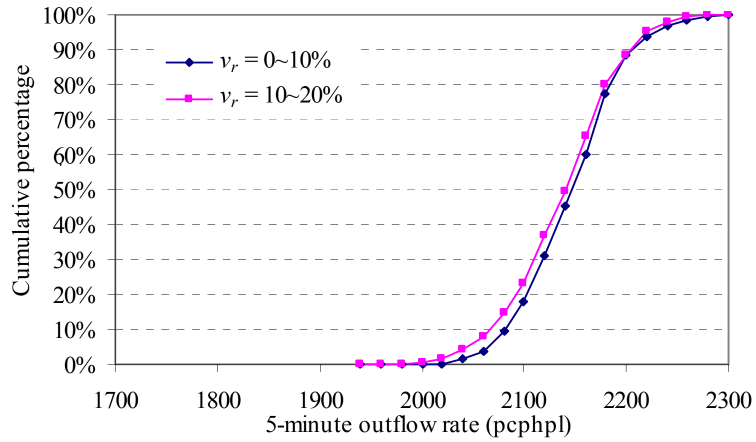



(b) Breakdown capacity versus *l*

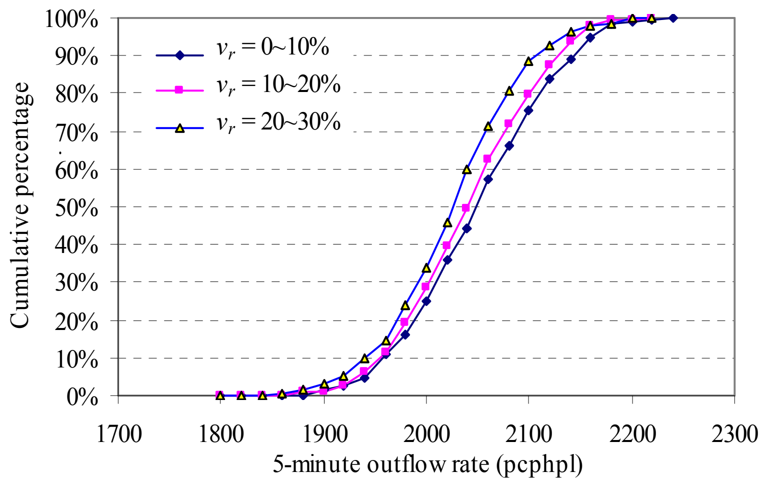



(c) Queue discharge capacity versus *l*

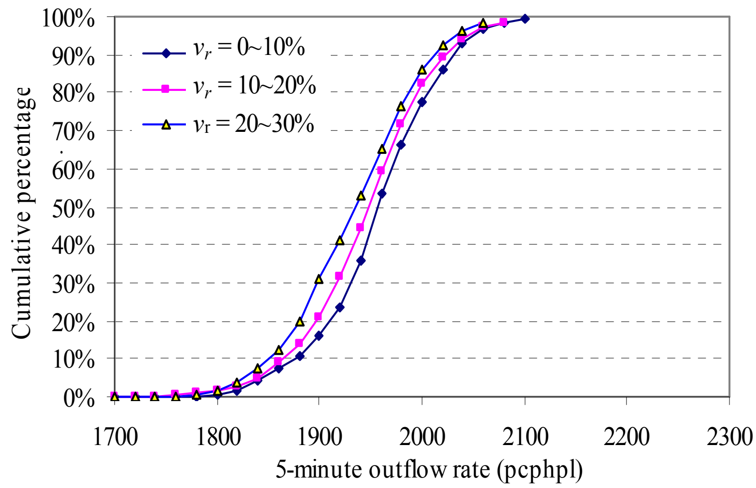
**Figure 8 The relationship between the 85% value of the three aspects of merging capacity distributions versus acceleration lane length *l*.**




a) Maximum pre-breakdown capacity distributions




b) Breakdown capacity distributions




c) Queue discharge flow distributions

**Figure 9 The cumulative distributions of the three aspects of merging capacity with different values of ramp flow ratio**

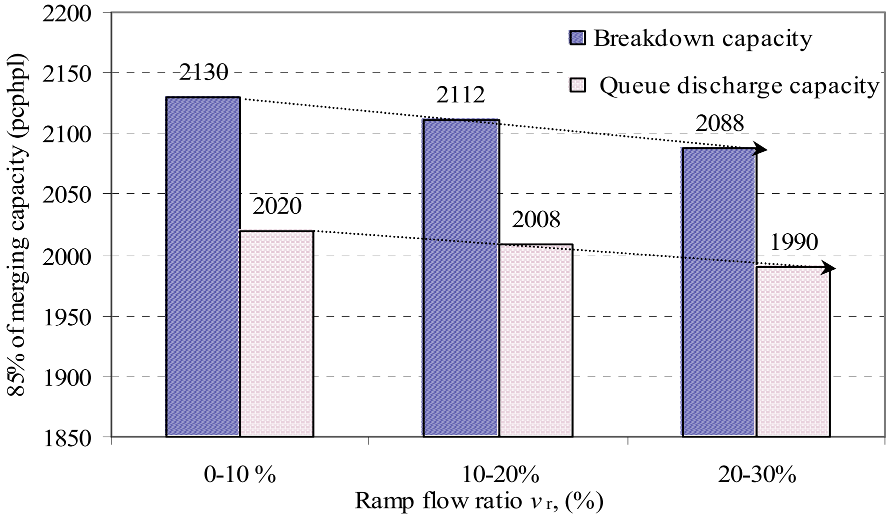



**Figure 10 The 85th percentile values of capacity distributions at different levels of ramp flow ratio**