A Lane-Based Analysis of Stochastic Breakdown Phenomena on an Urban Expressway Section

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Abstract: In this study, stochastic breakdown phenomena on a two-lane section of a Japanese urban expressway are analyzed and modeled. Because the bottleneck of the subject section is supposed to be a complex geometry with an on-ramp, a horizontal curve and an uphill, analysis is conducted not only by cross section but also by lane to understand the characteristics of breakdowns in detail. For such a detailed analysis, applicability and limitation of the detector data with different aggregation intervals are also considered. Through the analysis, it is found that about 40% of breakdowns in the section occur first on the shoulder lane; one of the causes would be higher merging traffic volume. The estimation of breakdown probability shows that the capacity of the median lane is about 300-veh/h greater than that of the shoulder lane. Furthermore, it is found that the discharge flow rate deteriorates as the elapsed time after breakdown increases, especially at the beginning of congestion.

Keywords: Breakdown Probability, Discharge Flow, Urban Expressway, Detector Data

1. INTRODUCTION

Recently, the capacity of freeways has been recognized as not deterministic but stochastic (e.g., Lorenz and Elefteriadou, 2000; Okamura et al., 2000; Minderhoud et al., 1997; Elefteriadou et al., 1995). A number of studies have been conducted to model the distribution of capacity, which is also called “breakdown probability” since breakdown occurs when traffic volume exceeds capacity (e.g., Brilon et al., 2005; Minderhoud et al., 1997). A concept of breakdown probability plays an important role in evaluating the performance of a freeway and taking account of its reliability. Queue discharge flow during congestion (hereafter, referred to as discharge flow) has also been studied considering its stochastic nature (e.g., Ma et al., 2013; Sarvi et al., 2007). Since it somehow represents the capacity of congested flow and determines the duration of congestion, evaluation of discharge flow is also an important topic for freeway operation.

Until now, most of these studies were done for rather simple bottlenecks where only a single cause (e.g., sag, on-ramp or off-ramp) could be considered. However, urban expressways in Japan are designed with tight horizontal and vertical alignments because of limitation of land use, and they have more on-ramps and off-ramps with short spacing. In such bottlenecks, more frequent lane changing and merging/diverging behavior are expected.

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Differences in the traffic condition of individual lanes because of these microscopic behaviors seem to affect the stochastic breakdown phenomena strongly. Nevertheless, most of the previous studies on breakdown probability have been based on cross sections, and few analyses have examined differences between individual lanes. Therefore, in this paper, lane-based analysis is conducted to understand the stochastic characteristics of breakdown on an urban expressway in more detail. For such an analysis, applicability and limitation of the detector data with different aggregation intervals are also considered, because they strongly affect the reliability of the results in a section where the traffic condition changes in a short period. In the future, this kind of study is expected to contribute to more accurate and reliable prediction of breakdown and travel time by inputting breakdown probability and/or discharge flow rate in a macroscopic traffic simulator, for example.

This paper is organized as follows. In section 2, estimation methods of breakdown probability and some literature related to breakdown phenomena and discharge flow are reviewed. In section 3, a study site for analysis and modeling is introduced (3.1), then, methods for aggregating detector data (3.2) and identifying breakdown occurrence (3.3) are explained. In section 4, breakdown occurrence is analyzed. Here, not only characteristics of breakdown on different lanes, but also applicability of 1-min, 3-min, and 5-min aggregated data are discussed. In section 5, discharge flow after breakdown is analyzed and modeled. Finally, a conclusion and proposal for future work are offered in chapter 6.

2. LITERATURE REVIEW ON STOCHASTIC BREAKDOWN

The concept of stochastic capacity was first introduced by Brilon et al. (2005). They proposed two methods for estimating the distribution of capacity, which is called “breakdown probability” in this paper, by using observed traffic flow rates within predetermined intervals. One is a nonparametric estimation method—the so-called Product Limit Method (PLM)—which applies lifetime data analysis developed by Kaplan and Meier (1958) and Lawless (2003). In this method, breakdown probability can be estimated by the following equation (1):

\[
F_c(q) = 1 - \prod_{i; q_i \geq q} \frac{k_i - d_i}{k_i}; \quad i \in \{B\}
\]

where,

- \(F_c(q)\) : breakdown probability of \(q\) (distribution function of capacity \(c\)),
- \(q\) : traffic flow rate [veh/h],
- \(q_i\) : traffic flow rate in interval \(i\) [veh/h],
- \(k_i\) : number of intervals with a traffic flow rate of \(q \geq q_i\),
- \(d_i\) : number of breakdowns at a volume of \(q_i\), and
- \(\{B\}\) : set of breakdown intervals; observed intervals are divided into breakdown intervals in which traffic flow rate triggered breakdown and prebreakdown intervals. Intervals during congestion are not used. If \(i\) is categorized into breakdown intervals, \(q_i\) is called “breakdown flow rate”.

However, a complete distribution curve can seldom be obtained with the PLM. Therefore, another method that preassumes a type of distribution function is also proposed. In this method, the Weibull distribution (equation (2)) is usually adopted to represent the distribution function. As this method maximizes the likelihood function given by equation (3) to estimate parameters \(\alpha\) and \(\beta\), it is called the Maximum Likelihood Method (MLM):

\[
F_c(q) = 1 - \exp\left(-\left(\frac{q}{\alpha}\right)^{\beta}\right)
\]

\[
\ln(-\ln(F_c(q))) = \beta \ln(q) - \beta \ln(\alpha)
\]

\[
\ln(-\ln(F_c(q))) = \beta \ln(q) - \beta \ln(\alpha)
\]
\[ F_i(q_i) = 1 - \exp \left( -\left( \frac{q_i}{\beta} \right)^{\alpha} \right) \]  

(2)

\[ L = \prod_{i=1}^{n} f(q_i)^{\delta_i} [1 - F(q_i)]^{-\delta_i} \]  

(3)

where,

- \( f(q_i) \) : probability density function of breakdown probability,
- \( F(q_i) \) : breakdown probability of traffic flow \( q_i \),
- \( \alpha \) and \( \beta \) : shape parameter and scale parameter of the Weibull distribution,
- \( n \) : number of observations,
- \( q_i \) : traffic flow rate in interval \( i \) [veh/h], and
- \( \delta_i \) : dummy value of breakdown flow (\( \delta_i = 1 \): breakdown flow rate, \( \delta_i = 0 \): uncongested flow rate).

By using these models, several researchers have estimated the breakdown probability in various locations and conditions (e.g., Stralen et al., 2015; Kondyli et al., 2013; Brilon et al., 2007). However, as mentioned in the previous chapter, most of them are based on cross sections, and there has been very limited research dealing with lane-based characteristics of breakdown. As mentioned already, urban expressways in Japan typically have a tight geometry with frequent merging and diverging sections; thus, detailed lane-based analysis is necessary. In the past, with a similar motivation, Shawky and Nakamura (2009) modeled the breakdown probability at merging sections of the Tokyo metropolitan expressway but only through a cross-section approach because lane-based data were not available. Among the limited studies with a lane-based approach, Ma et al. (2013:1) analyzed diverging sections on Japanese intercity expressways and found that breakdown sometimes occurred only on the shoulder lane, or first on the shoulder lane and then on the median lane. This paper further investigates such characteristics on urban expressways, which might be more significant than on intercity expressways.

On the other hand, stochastic characteristics of discharge flow have also been found in some previous studies, such as Ma et al. (2013:2), Jia et al. (2010) and Brilon et al. (2005). It was widely known that the discharge flow rate becomes lower than the flow rate before breakdown, which is the so-called “capacity drop” phenomena. According to the analysis of Ma et al. (2013:2) on diverging sections in Japan, discharge flow rate decreases if the duration of breakdown increases. Yamaguchi et al. (2016) analyzed possible factors concerning the reduction of discharge flow rate by time, such as the duration of congestion, merging traffic volume, gradient, and ambient lighting conditions. However, the characteristics of discharge flow rate have not been analyzed for individual lanes.

In summary, consideration of differences in breakdown by lane has been limited in previous research, although cross-section analysis seems to oversimplify the traffic condition for understanding the stochastic characteristics of urban expressways where lane usage may differ significantly because of complex geometry.

3. DATA DESCRIPTION
3.1 Study Site

In this paper, a two-lane section of the Meinikan expressway, which is the outer ring motorway in the Nagoya metropolitan area in Japan was analyzed. Figure 1 shows the road network in Nagoya and the location of the study site. The horizontal and vertical alignment of this expressway is relatively tight and frequently changing, and on-ramps and off-ramps are placed relatively densely, as these are typical characteristics of an urban expressway. The subject section is in the northern part of the expressway. Figure 2 shows the geometry of the section. As shown in this figure, there are continuous changes of curvature, and on-ramps and off-ramps with short spacing. Because this section connects the semisubterranean section (left part of Figure 2) to the elevated interchange (Kamiyashiro-JCT), there is a tight uphill around 3.0 KP. A very high traffic volume is observed in this section during the morning peak on weekdays, as the main users are commuters. Therefore, almost all of the congestion on this section occurs from 6:30 to 7:00 am.

In this study, loop detector data for the whole year of 2014 were analyzed. Double-loop detectors are installed in each lane where red squares with kilometer posts (hereafter referred to as “KP”) are located in Figure 2. At these detectors, in addition to traffic volume counts,
average spot speeds of individual vehicles are measured based on the difference between passing times at the first loop and the second loop. Here, if a vehicle changes lanes when passing from the first to the second detector, it results in an error or a missing record. Then, traffic volume counts and average spot speeds are aggregated once every minute.

Because this study does not focus on the congestion caused by unusual incidents such as accidents, obstacles, roadwork, temporary traffic regulation, etc., such data were excluded. Furthermore, in order to exclude the impact of ambient lighting and weather conditions, which are also known to be a factor influencing traffic capacity, only the data from 5:30 to 11:00 am on sunny days were analyzed. Data from weekends and holidays were not used in this analysis, considering differences in drivers’ characteristics. In addition, all data that included errors or missing records were eliminated. After this data cleansing, 159 days were the subject of the analysis.

Through a preliminary analysis of the speed contour and flow-speed relationship in these data, it was found that congestion was observed from 2.83 KP to the upstream section in most cases. This result agreed with the previous analysis of probe vehicles around this section by Kimura et al. (2014), in which speed reductions were observed from 3.4 KP to 2.4 KP. As shown in Figure 2, the detector at 2.83 KP is located immediately downstream of the Hikiyama on-ramp on the uphill with a 3.1% gradient. Furthermore, there is a right-hand curve before the on-ramp. Such a complex geometric structure was considered to be the bottleneck of this section.

3.2 Aggregation of Detector Data

Brilon et al. (2005) mentioned that only rather short observation intervals are useful for understanding the causal relationship between traffic flow and breakdown. According to Brilon and Zurlinden (2003), a 5-min interval was the best compromise for obtaining reliable and useful results. However, for lane-based analysis of a section with merging traffic, a 5-min interval might be too long because macroscopic behavior such as merging and lane changing would affect the breakdown of each lane in a shorter time.

Therefore, in this paper, the original data with 1-min intervals were aggregated into not only 5-min but also 3-min intervals. Then, breakdown identifications were done for three types of dataset with 1-min, 3-min and 5-min intervals in order to verify the impact of aggregation intervals.

When aggregating 1-min data into 3-min or 5-min intervals, usually the beginning of a time intervals is based on the clock. For example, 5-min aggregation starts from 0:00 to 0:05 (more precisely, from 0:00:00 to 0:04:59) for the first interval of the day and continues until the last interval from 23:55 to 24:00. In this paper, we call this way of dividing time intervals “clock-based aggregation.” However, it is likely that uncongested and congested conditions are summed up into the same interval by clock-based aggregation. In other words, this method cannot always capture changes in traffic flow conditions precisely.

Therefore, in this study, not only clock-based aggregation but also another attempt to aggregate the data was made so that uncongested and congested conditions could be more reasonably divided, and the time of breakdown occurrence could be captured more precisely. First, aggregations were done for all possible time divisions. For example, for 5-min aggregation, five types of aggregation starting from the intervals of 0:00-0:05, 0:01-0:06, 0:02-0:07, 0:03-0:08 and 0:04-0:09 were conducted. Second, breakdown identifications were made for all five types of aggregation (the identification method is explained in the next section), so there were five alternative intervals to be regarded as the time of breakdown occurrence. Finally, the time of breakdown occurrence was identified as the interval that had
the largest speed drop. Hereafter, this way of aggregation is called “max. speed drop aggregation.”

3.3 Breakdown Identification

3.3.1 Criteria of breakdown

In many of the previous studies, breakdown identification was done by defining the threshold value of speed, which is called critical speed (e.g., Shawky and Nakamura, 2009; Brilon et al., 2005). It is known that critical speed is site specific, and therefore usually it is necessary to find the value that can appropriately divide uncongested and congested conditions (e.g., Jia et al., 2010, etc.)

However, after a preliminary analysis of the hysteresis of the flow-speed relationship for individual breakdowns, it was found that critical speed alone might not always be enough to identify breakdown, because in this section, there were some cases where the speed reduction was not significant around a certain value, which could be regarded as the critical speed in other cases. This might be because drivers could maintain their speed even under heavy traffic conditions in some cases, because they were used to driving on this section every day for commuting. To address this problem, it was found that adding criteria for the speed drop (the reduction of speed from the previous time interval) could make identification more reasonable. In fact, criteria for minimum speed drop were also applied in a previous analysis using 5-min detector data (Chen et al., 2004).

Thus, as a summary, in this study, breakdown was detected at the interval $i$ when all of the following three criteria were satisfied:

(a) speed ($v_i$) was below the critical speed,

(b) speed drop ($v_{i-1} - v_i$) was greater than a minimum value, and

(c) speed continued to be below the critical speed for 15 minutes or more.

The critical speeds were found to be 48, 58 and 53 km/h, and the minimum speed drops were 5, 8 and 7 km/h for the shoulder lane, median lane and cross section respectively, after testing several combinations of critical speed and minimum speed drop.

Here, although some previous studies such as Jia et al. (2010) have proposed the use of density for identifying breakdown, it was not applied in this study because it was found that breakdown sometimes did not occur even under high-density conditions (high speeds were maintained under heavy traffic flow), as mentioned above. Another reason is that density cannot be directly measured by loop detector data, and average spot speed is rather convenient considering its further practical application.

3.3.2 Definition of breakdown flow rate and discharge flow rate

Figure 3 shows the flow-speed relationship in 5-min aggregated data (clock-based), indicating their condition according to the above criteria. Traffic conditions in these figures are categorized into five types: (i) “breakdown” is the one satisfying the above criteria; (ii) “uncongested” is before breakdown; (iii) “prebreakdown” is immediately before breakdown in an uncongested condition; (iv) “congested” is when the speed is below the critical speed after breakdown; and (v) “after recovery” is when the speed becomes higher than the critical speed after a congested condition. It was recognized that some plots were not identified as “breakdown” even though the speeds were lower than the critical value, because their speed drops were too small.

Breakdown flow rate, which is assumed to be the trigger of breakdown, is defined as the flow rate when breakdown is identified (“breakdown” plots in Figure 3) in this paper, although some previous studies defined it as the one immediately before breakdown (“prebreakdown”). This is because, as shown in Figure 3, the flow rate of “breakdown” is
larger than that of “prebreakdown” in most cases. This is because the detector is located close to the bottleneck (even though the exact location of the bottleneck is not identified), and thus
there was a quite small time lag from when the flow that triggered breakdown passed the detector to when the speed reduction caused by the shock wave was observed at the detector. In that case, the whole of the abovementioned process of breakdown happened in the same time interval. In addition, the discharge flow rate is defined as the flow rate under the “congested” condition in Figure 3. Both breakdown flow rate and discharge flow rate are assumed to be stochastic and are analyzed in the following chapters.

Although it was not investigated in detail in this paper, one of the interesting findings from this figure is that speeds on the median lane “after recovery” were not as high as those of uncongested flow before breakdown. In other words, the density before breakdown was quite high (high traffic flow with high speed) compared with the flow after recovery on the median lane.

3.3.3 Impact of data aggregation on breakdown identification

Figure 4 shows an example of the breakdown identification with different ways of aggregating 5-min intervals, as explained in the previous section. The legend of this figure shows the interval at which aggregation started in the day. Namely, the black line “0:00-0:05” shows the data for the clock-based aggregation. In this figure, breakdown was identified at the interval of 6:40-6:45 in clock-based aggregation (black line), but it became the interval of 6:38-6:43 if max. speed drop aggregation was applied (red line). By referring to the 1-min speed profile (gray dashed line), it is recognized that max. speed drop aggregation can more precisely capture the time when the traffic condition changed from uncongested to congested.

4. ANALYSIS OF BREAKDOWN OCCURRENCE

4.1 Time Lag of Breakdown Occurrence

By applying the identification method explained in section 3.3, the numbers of breakdown occurrences based on the 1-min, 3-min and 5-min aggregated data are summarized in Table 1 for each lane and cross section.

By comparing the two aggregation methods in the same interval, more breakdowns can be identified by (b) the max. speed drop method than by (a) the clock-based method. The reason is that some breakdowns that recovered in a relatively short time sometimes could not be identified by clock-based aggregation because a congested condition at the beginning and/or the end was combined with an uncongested condition, and thus, the average speed could not be below the critical speed.
Actually, there were few cases where breakdown was identified on either the shoulder lane or the median lane alone. Such cases were mostly regarded as breakdowns when identification was done by cross section, and that is why the numbers of breakdowns by cross section are the highest in Table 1.

Even though breakdown was identified on both shoulder and median lanes, there was a time lag in their breakdown occurrence. To understand the mechanism of breakdown, breakdowns were categorized into the following three types by considering this time lag:

(i) StM: breakdown occurs first on the Shoulder lane, then on the Median lane,
(ii) SaM: breakdown occurs on both Shoulder and Median lanes simultaneously, and
(iii) MtS: breakdown occurs first on the Median lane, then on the Shoulder lane.

Figure 5 shows the share of each type of breakdown according to different aggregation intervals and methods. In this figure, it is recognized that the shares of three types of breakdown were similar in 1-min data and 3-min/5-min data by (b) max. speed drop aggregation. In these results, more than 40% of breakdowns were either “StM” or “SaM.” In general, breakdown on a basic segment tends to occur on the median lane first, but many breakdowns occurred on the shoulder lane first (StM) at this site. This may be because of merging vehicles from the on-ramp, as they are difficult to be observed by upstream vehicles because of the right-hand curve and the gradient.

However, the shares in 3-min/5-min data by (a) clock-based aggregation were quite different from the others, and fewer breakdowns were categorized into the type with a time lag in breakdown occurrence between the shoulder and median lanes (“StM” and “MtS”). This is because these time lags were smaller than the aggregated intervals (3 or 5 min) in most cases.

As one of the causes of the time lag in breakdown occurrence between the shoulder and median lanes, the traffic volume from the Hikiyama on-ramp was considered. However, a detector is not installed on this on-ramp segment. Therefore, on-ramp traffic volume was estimated for every 5 min by the simple calculation of equation (4), using data from the two
where,

- $t$: time interval (every 5 min),
- $q_{ON}(t)$: on-ramp traffic volume of time interval $t$ [veh/5 min],
- $q_{2.83}(t)$: traffic volume of time interval $t$ at 2.83KP [veh/5 min], and
- $q_{4.39}(t)$: traffic volume of time interval $t$ at 4.39KP [veh/5 min].

In this equation, it was assumed that all the traffic passing the upstream detector (4.93 KP) could reach the downstream detector (2.83 KP) in the same time interval, for simplicity. This is because the two detectors are close together (only 1.56 km apart), and a 5-min interval is long enough to ignore the time necessary to travel between the upstream and downstream detectors.

To see whether the inflow condition from the on-ramp affects the time lag in breakdown on different lanes, Figure 6 shows the estimated on-ramp traffic volume 5 min before the breakdown on the shoulder lane in two cases: the case where breakdown occurred first on the shoulder lane, then on the median lane (“StM”); and other cases (“SaM or MtS”). Here, the max. speed drop method was used to categorize the breakdown events into these two cases.

In this figure, the on-ramp traffic volume is greater in StM than in SaM or MtS. This can be interpreted as indicating that traffic flow from the on-ramp is likely to cause breakdown on the shoulder lane first, because it merges directly into it.

### 4.2 Breakdown Flow Rate

Figure 7 shows the distributions of the breakdown flow rate on the shoulder and median lanes with different aggregation intervals. It is clear that the longer the aggregation intervals are, the smaller the breakdown flow rates and the smaller their variation becomes. From this figure, a 1-min flow rate seems to be too fluctuating, and 3-min or 5-min flow rates would be better for analyzing the flow characteristics considering their reliability. In the following analysis of this paper, a 5-min flow rate is used because it has a smaller variation and is consistent with many of the previous studies.

Figure 8 shows the 5-min breakdown flow rate of individual lanes as well as a cross section, by two aggregation methods. It is found that a breakdown flow rate based on the max.
speed drop method is slightly greater with a smaller variation than one based on the clock-based method. This would also suggest that the max. speed drop method could capture the boundary between congested and uncongested traffic conditions more precisely. However, the figure also indicates that the difference between the two methods is not large. This means...
that the clock-based aggregation method can also provide reasonable information when analyzing traffic flows. Consequently, in the following part, breakdown flow rates and discharge flow rates based on the clock-based method are used for convenience.

4.3 Breakdown Probability

Breakdown probability—in other words, the capacity distribution function—is estimated not only by breakdown flow rate, as analyzed in section 4.2, but also by uncongested prebreakdown flow rate. This has been estimated according to the methods proposed by Brilon et al. (2005). When estimating breakdown probability, a complete distribution curve can seldom be obtained by the PLM, while the assumed type of distribution function is not guaranteed to fit well in the MLM. Therefore, to supplement these disadvantages, estimations are made by both the PLM and the MLM, as shown in Figure 9. Here, Weibull distributions are assumed in the MLM, and estimated parameters $\alpha$ and $\beta$ are also shown in the figure. In this figure, breakdown probability distributions by the MLM and the PLM are mostly
identical in both the shoulder and median lanes as well as the cross section. This means that the estimated Weibull distribution can reasonably represent the breakdown probability distribution.

Figure 9(a) shows that breakdown occurred more easily on the shoulder lane than the median lane. Based on the estimated Weibull distributions, the 5-min traffic flow rates that reach 50% of breakdown probability are 1601 and 1941 veh/h on the shoulder and median lanes, respectively. Thus, it is recognized that the capacity of the median lane is about 300 veh/h greater than that of the shoulder lane. This difference is almost the same as the difference between the observed breakdown flow rates in the previous section (Figure 8). In addition, it is also confirmed that the breakdown probability of the median lane is more wide-ranging than that of the shoulder lane. At this study site, because a majority of the users are daily commuters and probably know the traffic conditions at the site from experience, many of them prefer driving on the median lane in order to avoid conflict with, and/or giving way to, merging vehicles from the on-ramp. Such characteristics may have resulted in the difference in breakdown probability between the two lanes.

Figure 9(b) shows the breakdown probability of the cross section, which is more wide-ranging from 3000 to 3800 veh/h. From the estimated Weibull distribution, the flow rate that reaches 50% of the breakdown probability is 3495 veh/h. In fact, this is lower than the sum of the flow rates on the shoulder and median lanes (1601 + 1941 = 3542 veh/h). This suggests that the breakdown probability of the cross section might have been underestimated when the estimation was done based on the cross section.

5. ANALYSIS OF DISCHARGE FLOW

In this chapter, stochastic characteristics of discharge flow under congested conditions are analyzed. Figure 10 shows distributions of breakdown flow rates and succeeding discharge flow rates from 5 to 60 min after breakdown on the shoulder and median lanes. In this figure, it is indicated that the discharge flow rates decrease as the elapsed time after breakdown increases. As the elapsed time after breakdown increases, the queue length is expected to increase, and thus the duration of drivers’ being involved in congestion will also increase. This makes drivers demotivated to follow the leading vehicles and results in a decrease in discharge flow. According to Figure 10, decrease in discharge flow rates are greater at the beginning of congestion but seem to converge after around 40 min. This kind of phenomenon
is critical when predicting the duration of breakdown.

In order to represent this phenomenon considering its stochastic characteristics, the distribution of discharge flow rate is assumed to be normally distributed, and its mean and standard deviation (hereafter referred to as STDV) are modeled by the following exponential function.

$$x = \alpha \exp(-\beta t_{DC}) + \gamma$$

where,

$x$: mean $\mu$ or STDV $\sigma$ of discharge flow rate [veh/h],
$t_{DC}$: elapsed time after breakdown occurrence [min], and
$\alpha$, $\beta$, and $\gamma$: parameters.

Table 2 shows the estimation result of nonlinear regression for the parameters of equation (5). Note that the estimation was done by using 16 samples of the means/STDVs of discharge flow rate with the elapsed time from 5 to 80 min (every 5 min). Although the sample size of discharge flow rates for calculating mean/STDV became smaller as the elapsed time increased, more than 80 samples were obtained for each of the mean and STDV.

By using this model, Figure 11 describes the change of the mean and mean $\pm$ STDV of estimated discharge flow rates by the elapsed time after breakdown. The plots in the figure are based on the observed means and STDVs. It is confirmed that the estimated discharge flow rate can reasonably represent the actual tendency.

Figure 11 shows that discharge flow decreases more steeply on the median lane than on the shoulder lane as the elapsed time increases. The decrease in the mean of discharge flow rate from 5 to 30 min after breakdown is calculated as 114 veh/h (from 1487 to 1373 veh/h)
on the shoulder lane, whereas it is 158 veh/h (from 1811 to 1653 veh/h) on the median lane. Meanwhile, flow rates are always higher on the median lane than on the shoulder lane. This result agrees with the general tendency that more drivers like to drive on the median lane under congested flow. Especially in this section, this tendency may be stronger because drivers probably try to avoid conflict with merging vehicles on the shoulder lane.

6. CONCLUSION

In this paper, lane-based analysis was conducted to understand the stochastic characteristics of breakdown on a section of an urban expressway with complex geometry. The main findings on the characteristics of breakdown phenomena are summarized as follows.

- Breakdown on the section with an on-ramp sometimes occurs from the shoulder lane first. In the subject section, about 40% of breakdowns represent this case; one of the possible causes of this type of breakdown is considered to be a high volume of merging traffic.
- The capacity of the median lane is greater than that of the shoulder lane. In the subject section, the flow rate that reaches a breakdown probability of 50% was about 300 veh/h greater on the median lane than on the shoulder lane.
- The discharge flow rate decreases as the elapsed time after breakdown increases, especially at the beginning of congestion, but it seems to converge after a certain duration (40 min in the subject section). The discharge flow rate on the median lane decreases more steeply with elapsed time than that on the shoulder lane. However, the flow rate is always greater on the median lane than on the shoulder lane.

In addition, through the analysis, applicability and limitation of the detector data were considered, and the following was found.

- Aggregation of the detector data based on the clock cannot capture the change of traffic condition from uncongested to congested appropriately, as the aggregation intervals are longer. As a result, 3- and 5-min intervals are too long to detect a time lag in breakdown occurrence between individual lanes. In order to capture this precisely, aggregation should start from the time when maximum speed drop around the critical speed is observed.
- The breakdown flow rate is slightly lower when aggregation is done based on the clock compared with when it is done based on the time of maximum speed drop, but the clock-based method is still useful because the difference is small.

Because the above findings are based on a single section, more analysis must be conducted in other sections in the future, so as to verify and generalize the characteristics of breakdown on urban expressways. Another future work would be a consideration of the interaction between breakdowns on individual lanes, because this study analyzed and modeled stochastic breakdown on shoulder and median lanes independently. These will help us to understand the mechanism of breakdown better and will enable more reliable breakdown prediction.

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REFERENCES


