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Abstract

We developed the Kittler+ method, in combination with image enhancement method and Kittler's method of image binarizing, which automatically determines critical speeds that discriminate congested vehicular flow from uncongested flow, based on online vehicle detector data collected on Tokyo Metropolitan Expressways. Then, we expanded our method in order to appropriately extract critical conditions of vehicular flow by its two time applications to the data collected by sensors installed at a single cross-section in the vicinity of the bottleneck. We estimated mean bottleneck capacity values of daytime and nighttime, of dry days and rainy days, and of weekdays, Saturdays and holidays, from the extracted data. Except for situations of insufficient number of observations, significant influences of the situations to the bottleneck capacity were found.

Keywords: CONGESTION, TRAFFIC SIMULATION, CRITICAL SPEED, TRAFFIC CAPACITY, BINARIZE, THRESHOLDING

Introduction

On urban expressways in Japan, there is a chronic problem of traffic congestion, which results in the loss of travel time and causes safety and environmental problems. When traffic congestion occurs, the traffic control center for the Tokyo Metropolitan Expressways (MEX) executes various countermeasures to ensure traffic control and to pass traffic information to the road users. If the traffic congestion is due to the excess of the traffic demand over the capacity of the bottleneck, it can be predicted beforehand using statistical data accumulated over a long period of time. However, traffic congestion due to incidents like traffic accidents is difficult to predict through the use of the statistical method because locations, capacity, and duration of traffic congestion, and route choice conditions are totally different from usual ones. In the same way, it is very difficult to predict the occurrence of accidents. However, if traffic conditions after the occurrence of such incidents can be predicted, then the loss due to the traffic congestion can be reduced by, for instance, providing adequate and timely detour information.

In recent times, a simulation system that predicts short-term future conditions of traffic after occurrence of an incident has been developed. The simulation uses on-line data obtained from traffic detectors. At that time, traffic capacity at the locations of the incident that causes traffic congestion is directly measured using the vehicle detectors installed at the location. In addition, the duration of the traffic regulation at the location of the incident are predicted

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according to the traffic conditions. As a result, the traffic capacity at the temporary bottleneck are set to the traffic simulation system as one of the important parameters.^{1), 2)}

On the other hand, traffic capacity of other potential bottlenecks is also important parameters that affect the precision of the traffic simulation because the detour traffic from the incident location to the bottlenecks may cause other congestion. However, the capacity of the potential bottlenecks sometimes cannot be directly measured at the commencement of the traffic simulation because it may take a certain period of time for the detour traffic to reach to them and to cause other congestion.

Therefore, the traffic capacity of the potential bottlenecks must be set up in advance using historical data. Moreover, the locations and the traffic capacity of potential bottlenecks should be assumed to vary over the short term or medium term owing to factors such as the construction of new links and changes in lane configurations. Therefore, these parameters must be regularly updated.

To set up and update the capacity of bottlenecks, we need to acquire traffic volume during critical conditions. Namely we have to observe traffic volume not just at the locations of bottlenecks but at the upstream ends of the traffic congestion. The critical conditions can be identified by linking congested road segments as the upstream ends of the traffic congestion based on vehicle detector data. However, a point between upstream and downstream ends of congestion may also be incorrectly identified as a bottleneck due to insufficient precision of sensing traffic congestion based on traffic detector data. Moreover, because more than 2,500 vehicle detectors have been installed on the main lines of Tokyo Metropolitan Expressways, it is difficult to manually identify bottlenecks and estimate traffic capacity of the entire network of Tokyo Metropolitan Expressways.

In this study, we propose a technique of extracting traffic volume at the upstream ends of traffic congestion by applying a method for determining critical speed that discriminate congested conditions from uncongested ones from accumulated traffic detector data. This technique can also be applied to determine the bottleneck capacity of daytime and nighttime, of weekdays and holidays, and of dry days and rainy days.

Existing research

In this study, a method of automatically identifying bottlenecks has to be developed because the locations of bottlenecks change by conditions of roads and traffic, as mentioned above.

Koshi et al.^{3),4)} found discontinuities of car-following behavior between free flow region and congestion flow region by some experiments on a test track and by some observations of speed profiles on a real motorway. As a result, they also found some gaps in volume and speed observations between the two regions. *Koshi et al.*³⁾ suggested that traffic congestion could be detected by the critical speeds that were set in the middle of the gaps.

Akahane et al.⁵⁾ proposed a technique of sensing traffic congestion by comparing observed speeds with critical speeds that had been determined for each time of day and location. Akahane et al.⁵⁾ and Furukawa et al.⁶⁾ reported that the critical speeds should be assumed to change by locations not only due to characteristics of traffic flow but also due to differences in characteristic of vehicle detectors. Therefore, Otsu's⁷⁾ method that is used for image binarizing was applied to histograms of vehicle speeds in order to determine critical speeds⁵⁾.

A technique using Otsu's method fixes the threshold values as critical speeds that maximize variation between two classes of observations divided by critical speeds. A temporary location of the head of congestion due to an accident that took place about 1.7 km upstream of the ordinary bottleneck was clearly detected with the critical speeds⁵⁾. However, these studies adopted additional processes because of insufficient precision of setting critical speeds.



Fig.1 Route#3 (Shibuya line) of Tokyo Metropolitan Expressways

Recently, in addition to Otsu's method, some techniques for image binarizing have been developed⁸⁾. In this study, Kittler's method⁹⁾ was compared with Otsu's method from viewpoints of applicability of setting critical speeds.

*Furukawa et al.*¹⁰⁾ proposed a way of automatically tuning up the bottleneck capacity that minimized estimation errors in time that was taken to pass through traffic congestion. This method adjusted the capacity in an off-line convergence process by repeating simulation. However, because the traffic capacity is directly observed, optimization without a traffic simulation is effective when we think setting values of other parameters that can be only observed indirectly.

 $Bransto^{11}$ and $Buckley^{12}$ proposed methods of estimating capacity with headway-time supposing that traffic flow consisted of leader cars followers. However, it is not necessarily practical that headway-time is acquired with pulse data from a lot of vehicle detectors that this study should manage. *Hyde et al.*¹³⁾ estimated capacity as expected extreme values, as well as asymptotic values, supposing that traffic volume conformed to a certain probabilistic process.

However, bottleneck capacity should be estimated not as extreme values but values that

balance Type 1 errors with Type 2 errors of occurrence of traffic congestion in their online practical application to traffic simulation. If we can extract capacity observations as traffic volume not just at the locations of bottlenecks but at the upstream ends of the traffic congestion, we can determine the balanced capacity values based on them.

Vehicle detector data

In this study, we used 5-minute detector data, which consisted of traffic volume and speeds, collected at about 2,500 cross sections of Tokyo Metropolitan Expressways. The data were collected over a period of approximately three months from December 16, 2009 to March 26, 2010.

Fig. 1 shows the route #3, called Shibuya line, of Tokyo Metropolitan Expressways. In the outbound lane toward *Yoga* from the *Tanimachi* junction, there is a bottleneck caused by weaving and a sag, where traffic congestion frequently occurs, in the B



Fig. 2 Volume–Speed Relationships

(*Ikejiri*) section.

Fig. 2 shows the relations between traffic volume and speeds of the three sections shown in Fig. 1. The A (takakicho) section is at upstream of a bottleneck, and the observations of uncongested flow and congested flow are clearly divided. In addition, there are no observations of critical conditions. The B (Ikejiri) section, where observations of critical conditions can be found at the summit of the distribution of the



Fig. 3 Determination of critical speed image using Kittler's method

observations of Fig. 2, is near the bottleneck causing the traffic congestion. The C (Yoga) section, where no congested flow is observed most of the time, is at downstream of the bottleneck. It results in a biased distribution of observations in a high speed region.

Determination of critical speeds

Fig. 3 shows an image of determining a critical speed using the Kittler's method in this study. Originally, The Kittler's method chooses a threshold value that minimizes the probability of classification error, supposing that gray scale of an object as well as its background normally distributes. In this study, the Kittler's method was applied to frequency of detected speeds of both uncongested flow and congested flow, supposing that each of them normally distributes. Namely, a critical speed *k* is obtained as a value that minimizes a criterion J(k) of Equation $(1)^{9}$.

$$J(k) = \omega_1(k) \log\left(\frac{\sigma_1(k)}{\omega_1(k)}\right) + \omega_2(k) \log\left(\frac{\sigma_2(k)}{\omega_2(k)}\right)$$
(1)

where

i := 1(congested flow), = 2(uncongested flow)

k: threshold speed rank

v: speed rank

 v_{max} : maximum speed rank

h(v): frequency of speed rank v

$$N : \sum_{\nu=1}^{\nu_{\text{max}}} h(\nu), \ p(\nu) = h(\nu) / N$$

$$\omega_{1}(k) = \sum_{\nu=1}^{k} p(\nu), \quad \omega_{2}(k) = \sum_{\nu=k+1}^{\nu_{\text{max}}} p(\nu)$$

$$\overline{v}_{1}(k) = \sum_{\nu=1}^{k} v p(\nu) / \omega_{1}(k), \quad \overline{v}_{2}(k) = \sum_{\nu=k+1}^{\nu_{\text{max}}} v p(k) / \omega_{2}(k)$$

$$\sigma^{2}_{1}(k) = \sum_{\nu=1}^{k} (\nu - \overline{v}_{1}(k))^{2} p(\nu) / w_{1}(k), \quad \sigma^{2}_{2} = \sum_{\nu=k+1}^{\nu_{\text{max}}} (\nu - \overline{v}_{2}(k))^{2} p(\nu) / \omega_{2}(k).$$



Fig. 4 Comparison of critical speed by Otsu's method, Kittler method and Kittler+ method





The Kittler's method gives a better threshold value than the Otsu's method and other maximum likelihood thresholding methods when frequency of a class is extremely larger than that of another class¹⁴. Namely, the above characteristic of the Kittler's method takes an advantage when a critical speed is determined at a cross-section where traffic congestion rarely occurs like section C of Fig.2.

The detector data become outliers when they change between congested flow and uncongested flow over an observation period of 5 min. We adopted a method that excludes outliers additionally. This method adds the frequency of the traffic volume in each speed class, and removes observation data for

frequencies less than a constant ratio for the largest frequency. This is equivalent to edge enhancement in image processing.

Fig. 4 illustrates an example of the effect of this process. By making a comparison before and after the edge enhancement, the distribution domain for the low volume disappears and that for the high volume is emphasized. The exclusion result seldom depended on the ratio of edge emphasis, and we set it to be 30% in this study.

Fig. 4 shows the results of the calculation of the critical speed using Otsu's method, Kittler's method, and the method that is a combination of Kittler's and the edge enhancement methods ("Kittler+" Method). In sections A and B, there was not much difference in the results obtained using the Otsu's and the Kittler+ methods. However, it was determined that the Kittler+ method can be used to set a critical speed that is more appropriate than the Otsu's

method because the Kittler+ method is set on a lower part of the speed histogram than Otsu's method.

In section C, the Otsu's method set a critical speed inappropriately in the uncongested flow region. On the other hand, the Kittler+ method set a threshold value precisely between the congested flow region and the uncongested flow region. This result means that the Kittler+ method can determine appropriate threshold values without additional processing even at locations where congestion seldom occurs. However, in these sections, the critical speed values became the same both with and without edge enhancement. The effect of the removal of the outliers on the improvement in precision was not confirmed.

Fig. 5 shows traffic congestion that was detected by the current traffic control system on radial inbound line #3 of the Tokyo Metropolitan Expressways on 18th Jan. 2010. The upstream end of the congestion passed through the cross-section #540 at around 17:40 and 20:00.

Fig. 6 illustrates a trace of speed-flow rate relationships of the cross-section #540. The trace crossed the line of critical speed of 52 km/h set by the Kittler+ method at around the same time as the upstream end of the congestion passed through the section. This corresponds to the global change in the traffic conditions of the radial inbound line #3 shown in Fig. 5.

Setting of bottleneck capacity

Bottleneck capacity is an important parameter that is used to predict traffic congestion situation and travel time using the traffic simulation in this study. As reported by *Warita et al.*¹⁵⁾ and *Watanabe et al.*¹⁶⁾, in volume-speed planes, we can find distribution areas called the "capacity balls" at downstream adjacent sections to bottlenecks. The widths of the distribution areas of the direction of traffic volume indicate the fluctuations in the bottleneck capacity. In addition, they reported observed examples in which the traffic capacity fluctuated from several percent to more than 10% between dry days and rainy days, between daytime and nighttime, and between weekdays and holidays.



Fig. 6 A trace of speed-flow rate relationships on radial inbound line #3 of the Tokyo Metropolitan Expressways on 18th Jan. 2010



Fig. 7 Extracted critical state and setting of bottleneck capacity

In the vicinity of the bottlenecks where upstream ends of congestion frequently exist, there is very more number of the observation data of uncongested flow and critical flow than the observation data of the congested flow. Therefore, as in section B of Fig. 4, it is expected that the threshold speeds set in the vicinity of the bottlenecks by the Kittler+ method are located in



Fig. 8 Comparison of an identified bottleneck and detected speeds

the high-speed side of the capacity ball. On the other hand, the threshold speeds are at the borders with uncongested flow and congested flow at sections, such as section C, where no critical state exists and even where very little traffic congestion occurs.

Therefore, firstly, the observation data of the critical conditions as well as congested conditions is to be extracted when the Kittler+ method is applied at the bottlenecks. Then, it is expected that the observation data of the critical conditions is extracted by applying the Kittler+ method to these data again.

In this way, the algorithm that estimates the bottleneck capacity can be effectively applied to automatically initialize and update them.

In the example of Fig. 7, a critical domain was set between 33 km/h and 55 km/h using this procedure.

Fig. 8 shows a result of extracting the critical conditions based on vehicle detector data of the MEX outbound #3 Shibuya line collected in Jan. 18th, 2012. In this figure, the traffic congestion conditions provided by the Kittler+ method are red, and the critical conditions

Sort of days	daytime and nighttime	rainfall	Number of data	Estimated bottleneck capacity[ver/ h]	*1	*2
weekday	daytime	no rain	1276	2889.3	100.0	_
		rain	52	2743.6	95.0	0.0000
	nighttime	no rain	4009	2801.5	97.0	0.0000
		rain	177	2658.7	92.0	0.0000
holiday	daytime	no rain	401	2877.3	99.6	0.3386
		rain	3	2716.0	94.0	0.0519
	nighttime	no rain	551	2718.0	94.1	0.0000
		rain	2	2801.5	97.0	0.0055
Saturday	daytime	no rain	1020	2829.1	97.9	0.0000
		rain	13	2654.8	91.9	0.0000
	nighttime	no rain	824	2779.8	96.2	0.0000
		rain	2	2736.0	94.7	0.1606

 Table 1
 Decreases in bottleneck capacity due to situations

*1 shows the relative ratio of the bottleneck capacity under other situations to that under the standard situations.

*2 shows significance probability p of statistical t-test of differences in mean values of the bottleneck capacity under standard situations and under other situations.

provided by two time applications of the Kittler+ method are yellow. The critical conditions were appropriately detected by the proposed method based on the data collected by sensors installed at a single cross-section in the vicinity of the bottleneck.

Table 1 shows the mean values of traffic capacity of the bottleneck illustrated in Fig. 8. As mentioned before, bottleneck capacity should be estimated as values that balance Type 1 errors with Type 2 errors of occurrence of traffic congestion in their on-line practical application to traffic simulation. However, here, bottleneck capacity was estimated as mean values in order to evaluate influences of the situations by comparison.

These are mean values of daytime and nighttime, of dry days and rainy days, and of weekdays, Saturdays and holidays. The 'daytime' was set from time of the sunrise to the time of the sunset, and the 'nighttime' was set from time of the sunset to the time of the sunrise. The 'rain' means that there was recorded rainfall in excess of 0mm, and the 'no rain' means that there was no rainfall record.

First, the standard situations were defined as cases without the rain during daytime on weekdays. *1 in Table 1 shows the relative ratio of the bottleneck capacity under other situations to that under the standard situations. *2 in Table 1 shows significance probability p of statistical t-test of differences in mean values of the bottleneck capacity under standard situations and under other situations. For instance, rain decreased the bottleneck capacity by 5% during daytime and nighttime relative on weekdays. The capacity of night time decreases by about several percent from that of daytime. Except for situations of insufficient number of observations, the values of significance probability p were very small. That means significant influences of the situations to the bottleneck capacity.

In this analysis, there were some insufficient numbers of situations. However, we expect to obtain sufficient observations in order to set appropriate capacity values in a long period of time, if necessary, through the operation of the simulation system.

Conclusions

We developed the Kittler+ method, in combination with image enhancement method and Kittler's method of image binarizing, which automatically determines critical speeds that discriminate congested vehicular flow from uncongested flow, based on online vehicle detector data collected on Tokyo Metropolitan Expressways. The Kittler+ method can determine appropriate threshold values without additional processing even at locations where congestion seldom occurs in comparison with existing technique such as Otsu's method.

Appropriate values are not completely set by the above method automatically. Therefore, it will be necessary to add an algorithm of detecting and alarming outbreak of a few inappropriate setting results in order to correct them by manual operation.

Then, we expanded the Kittler+ method in order to appropriately extract critical conditions of vehicular flow by its two time applications to the data collected by sensors installed at a single cross-section in the vicinity of the bottleneck.

We estimated mean bottleneck capacity values of daytime and nighttime, of dry days and rainy days, and of weekdays, Saturdays and holidays, from the extracted data. As a result, rain decreased the bottleneck capacity by 5% during daytime and nighttime relative on weekdays. The capacity of night time decreases by about several percent from that of daytime. Except for situations of insufficient number of observations, significant influences of the situations to the bottleneck capacity were found. In a practical sense, bottleneck capacity should be estimated as values that balance Type 1 errors with Type 2 errors of occurrence of traffic congestion in their on-line application to traffic simulation.

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