Initiation of Queued Traffic Flow at Capacity Bottlenecks on Basic Expressway Sections*

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Synopsis

The characteristics of the traffic flow at capacity bottlenecks on Japanese expressways and in particular traffic flow phenomenon before and after queued traffic flow are analyzed. The capacity flow rate of the bottlenecks is analyzed empirically. The capacity flow rate at bottleneck activation is found to vary significantly, and bottleneck activation does not always occur even at the highest flow rate. The characteristics of state variables for each vehicle (headway, speed, converted flow rate and converted density) are analyzed for several sites around basic section bottlenecks using image-processing techniques. A method to identify the initiation of queued traffic flow using state variables and which can be applied without a definitive speed threshold, is proposed and shown to offer an improvement in performance compared with existing methods.

1. Introduction

Many capacity bottlenecks are activated on the Japanese expressway system and the resultant cost to society is high. Half of the traffic congestion is caused by excess demand at basic sections such as sag vertical curves and the entrances to tunnels [1]. Driving behavior and in particular car-following behavior is believed to cause this type of bottleneck phenomena [2], [3], [4].

In Japan, more drivers tend to use the passing lane as traffic volume increases. This results in the creation of long and dense platoons in the lane. When a platoon passes over a sag vertical curve, the speed of the leaders is reduced slightly by the increase in gradient and insufficient acceleration. This drop in speed generates a deceleration shock wave, which is amplified as it propagates backwards, resulting in the drivers in the tail of the platoon almost stopping. If the next platoon arrives before the drivers in the tail start to move again, bottleneck activation and queued traffic flow condition occurred i.e. a breakdown of traffic system occurs in the lane. Drivers just upstream of the blockage may try to switch to the outer lane(s), resulting in a queued traffic flow condition across the entire section.

Bottlenecks in basic sections occur at traffic flows of about 3,000 vehicles/hour/2-lane for a 2-lane 1-direction roadway, which is substantially lower than the capacity of ordinary basic

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sections [5]. Not all sag vertical curves become capacity bottlenecks. The conditions (such as vertical alignment, horizontal alignment, sight condition, etc.) of the ones which do lead to bottlenecks have already been examined [6], [7]. The capacity after queued flow occurs upstream of the basic section bottleneck is not the same as that just before activation of the bottleneck, and is substantially lower at about 2,200 to 2,700 vehicles/hour/2-lane [4].

Japanese road and traffic management organizations installed vehicle detectors on many roadways [1]. Usually, these sensors collect and process the information into five minute aggregated data. Such data enables for the operators to draw a distinction between free and queued flow conditions. The Japan Highway Corporation (JH) manages almost all the inter-city expressways in Japan. The identification method adopted by the JH means that a capacity bottleneck is considered to be activated between two detectors when one detector reports an average speed less than or equal to 40 km/h and the downstream detector shows more than 40 km/h over a five-minute period. The lower speed segment is considered to be in a queued traffic flow condition. The segment is considered to be in a free flow condition when the average speed returns to more than 60 km/h.

Although traffic congestion information systems (variable message signs, on-board car-navigation system with VICS (Vehicle Information and Communication System, real time traffic information system), browser-phones, radio broadcasts etc.) are very popular in Japan, it is well-known that they are often subject to errors or delays. The reasons for these problems or delays are thought to be caused by the criteria for identifying capacity bottlenecks. This paper investigates the basic traffic characteristics when capacity bottlenecks are started at basic sections. Observation of driving behavior are performed and analyzed. Finally, a method to identify the occurrence of queued flow with state variables for each vehicle and which can be applied without a speed threshold is proposed.

2. Characteristics of Five-minute Flow Rate and Average Speed

2.1 Example of Typical Phenomena

Fig. 1 shows typical phenomena at three sites around a sag vertical curve capacity bottleneck. This bottleneck (called the 'Moto-Hachiouji sag') is located in a suburban area of the Tokyo Metropolis on the Chuo-expressway, which runs westbound from Tokyo through mountainous areas with two lanes in each direction. The Moto-Hachiouji sag bottleneck is activated in the early morning on almost all Saturdays or the first day of the holidays.

It is located from about 31 kilometer-post (KP, kilometers from the start-point of the Chuo-expressway) to about 32 KP. Observation sites were at 27.6 KP, 31.6 KP and 33.0 KP. There are no merging or diverging sections within 5 km upstream or downstream of the site. A main line toll plaza is located about 6 km upstream with an on-ramp.

The average speed both in the median and shoulder lanes at 31.6KP reduces to less than 50 km/h at 6:25 a.m. The rate of flow particularly in the median lane increases just before speed reduction (at 6:10 or 6:15) by a significant amount (more than 2,000 veh/h). At 6:10, 6:15 and 6:20, the flow rates, being more than 3,500 veh/h/2-lane, suggests high traffic demand, and causes breakdown of traffic system (speed slowing down). Therefore, it is suggested that the excess demand causes this breakdown.
Conversely, at 33.0 KP, the average speed for each lane is adequate (more than 70 km/h), and there is no reduction in speed. This location is therefore considered to be sufficiently downstream of the bottleneck. Although high flow rates of almost 4,000 veh/h/2-lane are achieved at 6:20 and 6:25 at 27.6KP, no significant speed reduction is observed before 6:35. At 6:35, the average speed decreases suddenly for each lane, and the front of the shock wave of queued flow formed between 31.6KP and 33.0KP, is considered to have arrived at 27.6KP. The high flow rate increases the speed of the back propagation of the shock wave.

Before the activation of the bottleneck, the flow rate in the median lane is always higher than that in the shoulder lane, and the maximum flow rate is from 3,000 to 3,500 veh/h/2-lane. After activation however, the flow rate for each lane becomes almost equal and the capacity flow rate after formation of the queue is reduced to between 2,200 and 2,700 veh/h/2-lane. The feature shown above is the general case and is applicable to almost all bottlenecks at basic sections [3], [4].

2.2 Definition of Queued Traffic Flow and Threshold Identification Method

The queued traffic flow condition is defined as the slowing down of the queuing condition formed upstream of a capacity bottleneck when traffic demand exceeds the capacity. It is entirely a restricted flow condition caused by the downstream bottleneck. The terms ‘congestion’ or ‘congested flow’ are not used in this paper because they imply the condition of non-queued flow and high-density, high volume traffic condition, not entirely restricted flow condition.

It is very difficult to identify the capacity of a bottleneck from observed data and determine
the traffic demand for the bottleneck section simultaneously. In addition, the capacity and demand are continuously changing. Therefore, bottleneck activation (or deactivation) and queued traffic flow occurrence (or cancellation) cannot be so easy to forecast from actual observation nor to be identified immediately.

(1) Study Location

The Chuo-expressway incorporates a vertical curve sag bottleneck (called the 'Torisawa sag') in the westbound direction. It is about 20 km far away from the 'Moto-Hachiouji sag'.

We examined all five-minute epoch information for the Torisawa sag from the year 1996. Thirty-two activations of this bottleneck occurred on twenty-four days. No unexpected incidents such as traffic accident, vehicle breakdown, and so on, occurred on these days.

(2) Applied Method for Identifying Threshold of Traffic Conditions

Fig. 2 shows a typical example of the relationship between flow rate and average speed from five-minute epoch data at 62.0 KP. It can be seen that the data can be classified into two distinct groups, the free flow condition and the queued flow condition. A statistical method for distinguishing between the queued and free flow conditions was proposed by Akahane et. al. [8]. Through this method, the threshold is calculated as 54 km/h in the case of Fig.2.

From Fig.2, the threshold could be established anywhere between 50 km/h and 70 km/h, the value 54 km/h must not be thought of as the definitive value. Therefore, there still exists room for improvement although this method for identifying the threshold value has the advantage of objectivity.

![Fig.2 Traffic Volume Versus Average Speed(62.0KP, westbound, Chuo-expressway)](image)

2.3 Actual Proportion of Queued Flow Occurrence

As the detector at 62.0KP is located just upstream of the Torisawa sag bottleneck, the observed flow rates can be thought of as the capacity of the bottleneck. When the average speed is reduced to a value less than the threshold, the flow rate in the last epoch above the threshold is denoted the 'queue initiated flow rate'. There should be a delay at the detector from the actual bottleneck
activation time because of aggregation time and distance between real position of the bottleneck and the detector. Therefore, the flow condition of the epoch prior to the last period of speed above the threshold should be also considered to be queue initiated flow.

Considering that queue initiated flow occurred thirty-two times of 5-minutes epoch, sixty-four occurrences of queue initiated flow must be analyzed. The frequency distribution of flow rate level of non-queued flow condition is examined for all twenty-four days and shown as bar chart in Fig.3. The sixty-four frequencies of 'queue initiated flow rate' are marked in the figure. The line chart represents the proportion of the frequency of queue initiated flow rate to all frequencies at every flow rate level, which is denoted the 'actual proportion of queued flow occurrence'.

It can be seen that the flow rate at bottleneck activation varies from 2,500 to 3,600 vehicles/hour/2-lane, these values of flow rate might be the capacity flow rate of bottleneck activation. The total frequency of flow rate level decreases and the 'actual proportion' increases as the flow rate increases. However, the 'actual proportion' is 0.50 at the highest existing flow rate level (300 vehicles/5-minutes/2-lane). One 5-minute-flow rate in the highest level is non-queued flow condition, but another initiates the queued flow condition. This tendency has been observed at other basic section bottlenecks [9]. There are some bottlenecks at which the 'actual proportion' reaches less than 0.10 even at the highest existing flow rate level [9].

Note that the 'actual proportion of queued flow occurrence' does not represent the probability of the occurrence of queue initiated flow, because the frequency under consideration only includes non-queued flow and queue initiated flow condition, and does not consider the flow condition after queue formation. Therefore, the 'actual proportion' represents the apparent value derived from the conditional probability only under condition that non-queued flow is
maintained continuously. The conditional probability should be different for each actual occurrence of queued flow. Therefore, it is a difficult process to identify the probability of occurrence of queued flow at each flow rate.

3. State Variable Characteristics for Individual Vehicle

3.1 Outline of Observations

Video imagery captured from cameras installed on overpasses was used to calculate vehicle headway data. When two imaginary sensors of vehicle passage are settled virtually on one video imagery, the time difference between the car appearing in the two virtual sensors and the distance between the cameras was used to calculate the speed of each vehicle. Traffic condition in the median lane is most important to analyze bottleneck activation phenomenon, it was only applied to the median lane.

The Moto-Hachiouji sag on the westbound Chuo-expressway and the Ayase sag on the eastbound Tomei-expressway were selected as suitable sites because of the high probability of queued flow. Nine days of observations were performed at the Moto-Hachiouji sag (in 1999, 2000), and six days at the Ayase sag (in 1999).

3.2 Conventional Method and Actual Phenomena

Fig. 4 shows an example of speed and flow rate observed, comparing the differences between 5-minute aggregation, 1-minute aggregation and individual speed and flow rate. Conventional methods for identifying the initiation of queued flow uses a 5-minute epoch and speed reduction.
to less than 40 km/h. Applying this method, the queued traffic flow condition is identified in the 5-minute period 14:50-14:55 in this case.

When applying the same identification criteria to 1-minute aggregated speed, the queue-initiated time changes to 14:30, more than twenty minutes earlier than the period using the conventional method. Observing the time variation of individual speeds, it is reasonable to identify 14:30 as the initiation time. Therefore, in this example, the conventional method can not define adequately the start of queuing.

The data also suggests that the definitive speed of 40 km/h may not have any significance for identifying the occurrence of queued traffic flow. If the detector location is close to the capacity bottleneck, the speed observed might become more increased. Therefore, the ideal method should not employ a definite threshold value of speed, and the individual information of each vehicle, such as individual headway, speed, and so on, should be utilized.

3.3 State Variables of Each Vehicle

An example of the state variable characteristics of each vehicle is shown in Fig. 5, which shows the condition just upstream section of the Moto-hachiouji sag bottleneck. The 'converted flow rate' is calculated as the reciprocal of headway, and 'converted density' is derived as the reciprocal of the product of headway and speed. Queued flow and non-queued flow are expediently distinguished using 40 km/h as the threshold in this figure.
The characteristics of flow-density-speed relationship shown in this figure do not resemble those of well-known flow-density-speed relationships [5]. In the case of non-queued flow, there are some vehicles with a high speed and significantly high converted flow rate (extremely low headway), and the correlation between flow rate and speed is not clear. The correlation between converted density and speed is also not clear in the non-queued flow condition. In the case of queued flow, no correlation between any state variables is observed.

3.4 Proposed Method to Identify Queued Flow

Only the relationship between converted flow rate and converted density in non-queued flow is found to be clear in Fig.5, and the relationship obviously becomes different from this relationship when the flow transitions to queued flow.

We investigated the relationship between flow rate and density for individual state variables in non-queued flow. The approximation function of eq. (1) is found to be appropriate for any of the relationships observed at other locations or on other dates.

\[
q = -0.6k^2 + 100k = -0.6(k - 91.7)^2 + 5041.7
\]  

where, \(q\) is the converted flow rate in vehicles per hour (veh/h), \(k\) is the converted density in vehicles per kilometer (veh/km). The constant 5041.7 represents the maximum value of \(q\) (\(q_{\text{max}}\)). The actual converted flow rate can exceed the value \(q_{\text{max}}\), but such a high value must be realized only in non-queued traffic flow conditions. When one vehicle takes the converted values of flow rate \(q_i\) and density \(k_i\), the number of density values satisfying equation (1) for a particular flow rate \(q_i\) is generally two. The smaller of the two is defined as \(k_{\text{calc}}\). The difference in \(k_{\text{calc}}\) and \(k_i\) is defined as \(D_i\) and denoted the 'density gap'.

![Fig.6 Relationship between Speed and Density Gap](image-url)
\[ D_i = k_i - k_{calc} \quad (q_i < q_{\text{max}}) \]
\[ = 0 \quad (q_i > q_{\text{max}} \text{ or } q_i = q_{\text{max}}) \quad (2) \]

Fig. 6 shows typical characteristics of 'density gap' with variations in speed. When the flow is non-queued flow, the density gap is always smaller than 20 veh/km, and can also be negative. Conversely, when the speed decreases significantly (the initiation of queued flow), the density gap increases significantly (might be more than 20 veh/km) and exhibits large variations. These characteristics were observed at all sites and on all dates.

Fig. 7 shows the concept of the density gap method. The flow-density curve of equation (1) and the curve with a density gap of 20 veh/km (as a temporal expedient) are shown. The 40 km/h and 60 km/h lines, which are straight lines passing through the origin, are also shown. The shaded area represents the queued flow condition with a threshold of density gap of 20 veh/km. The striped area represents the difference between the proposed density gap method and the conventional method using a speed 40 km/h. In a relatively high flow, the density gap method could identify queued flow occurrence even if the average speed is higher than 40 km/h. This feature is advantageous for identifying queued flow condition near to the location of capacity bottlenecks on basic section.

Fig. 8 shows the difference of epochs in identifying the occurrence of queued flow between conventional method using 5-minute epochs and the density gap method for successive individual vehicles having a density gap greater than 20 veh/km. The density gap method can
always identify the occurrence at almost the same time or earlier than the conventional method. A difference of zero to five minutes is not significant because the method using 5-minutes epochs have only five minutes time resolution. The figure shows that a difference of more than twenty-minute earlier exists in several cases. Such early identification includes a temporal speed reduction situation. The situation means that queued flow is appeared very shortly after the initiation and immediately canceled. To avoid identifying such a short period of queued flow, the time-varying demand condition should be monitored at the neighboring upstream detector.

4. Conclusions

Bottlenecks at basic sections such as sag vertical curves are widespread in Japan. There are many programs for alleviation of capacity bottlenecks, they might become success or failure. There will still exist some capacity bottlenecks on expressways in the future.

This paper shows the basic characteristics of traffic flow and speed around bottleneck sections. However, individual driving behavior should be investigated because bottleneck activation is mainly caused by the characteristics of individual drivers. Individual headway and speed were observed, and a fast method for the identification of initiation of queued flow is proposed with individual state variables.

The applicability of the proposed method will be verified in future research. More sophisticated and objective methods will also be considered. The proposed method is labor-intensive and more intelligent and autonomous measures are needed.

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