IDENTIFICATION OF CAPACITY BALLS AND ANALYSIS OF AFFECTORS OF CAPACITY ON TOKYO METROPOLITAN EXPRESSWAY

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ABSTRACT
In the speed-flow relationship at a bottleneck, it has conventionally been recognized that the congested-flow region and the free-flow region appear on a parabolic curve. However, there should be no congested-flow region at a “true” bottleneck; aggregated data would gather as a prolate ellipsoid cluster around critical speed.
Numerous data was examined at the two well-known bottlenecks on Tokyo metropolitan expressway. Researchers demonstrated that the true bottlenecks exist downstream of the points currently recognized as the bottlenecks and identified the “capacity ball”s. The shapes of the capacity balls are prolate elliptic, which means the traffic capacity widely ranges at the bottlenecks. Three factors for fluctuation were identified and then quantitatively analyzed in this study.

1. INTRODUCTION

There are several cases in which the congestion determination speed for information provision on the traffic control system is used for bottleneck determination, even though this speed is less than the critical speed defined in traffic engineering. As a result, it is possible that the road sections currently recognized as bottlenecks may not be true bottlenecks.
In existing reference books (1)(2) on traffic engineering, the data in the congested-flow region appear in the speed-flow relationship diagrams of the bottlenecks. However, as the bottlenecks exist at the most downstream end of the congested zone, the data should distribute only in the free-flow and critical regions, except data during congestion due to accidents or constructions.
The data, therefore, does not distribute in the congested-flow region, and a prolate elliptic cluster of data named “capacity ball” appears adjacent to the critical speed between free-flow and congested-flow regions. In this paper, we first specify the correct positions of the bottlenecks.
Traffic capacity is one of the indicators that show the fundamental performance of a road network. The smallest capacity in a section forms a bottleneck. The traffic capacity at a bottleneck (hereinafter referred to as 'bottleneck capacity') may vary with various conditions other than the road structure. The bottleneck capacity is considered to decrease especially during rainfall times, nights, or holidays. For example, Warita and his group (3) have clarified that traffic capacities are

decreased by rainfall, brightness or day of the week respectively, by identifying bottlenecks and critical conditions at the bottlenecks. Moreover, Otani and his group (4) have born out that traffic capacity decreased approximately 8% with a rainfall of around 1 to 5 mm/h, tabulating fluctuation of traffic capacities at various rainfall levels.

It would improve traffic environments, such as reducing congestion or providing traffic information that would enable various countermeasures to be taken, by clarifying the characteristics of the bottleneck capacity. For example, inflow regulation to maximize the bottleneck capacity at entrance merging points may be renewed. Where about 36% of congestion is generated on Tokyo metropolitan expressway (3), it may be improved considerably. Moreover, the accurate prediction of congestion and travel time by traffic simulation may also be improved, in which one of the important input parameters is the bottleneck capacity.

Here we report the results of detailed quantitative analysis on fluctuation of traffic capacities influenced by various factors.

2. IDENTIFICATION OF CAPACITY BALLS

2.1 Objective Bottlenecks Studied

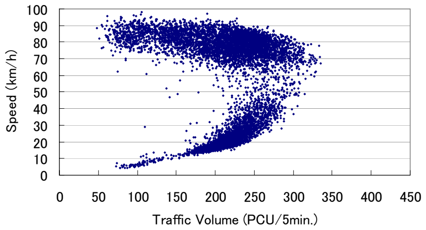
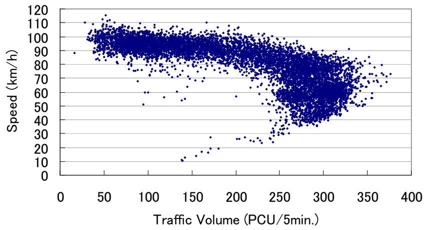
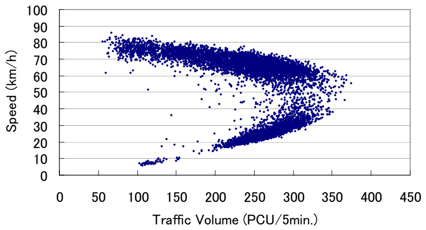
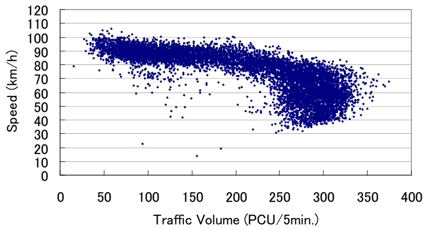
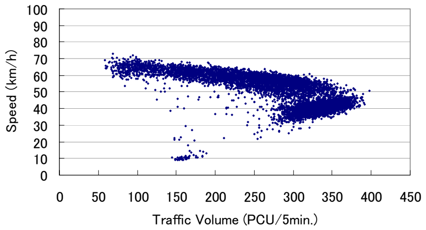
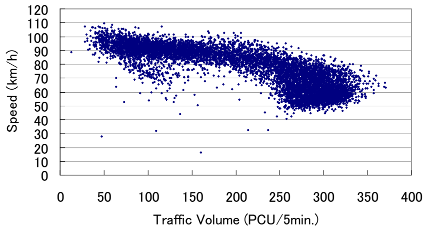
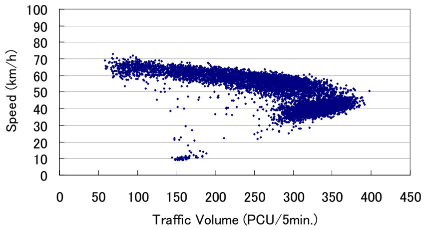
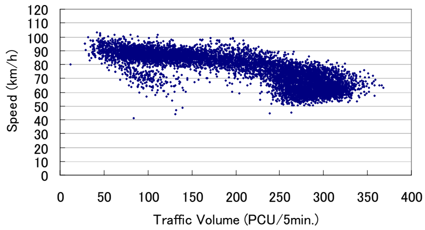
Based on the identification of bottleneck zones in the east Tokyo area of Tokyo metropolitan expressway (with total length of approximate 220km) (5), we studied the two well-known bottlenecks at merging points on Tokyo metropolitan expressway in this study. One of these bottlenecks is the merging point from Hakozaki rotary (outbound Route No.6 (Mukojima)), and the second is at Funaboribashi on ramp (outbound Central circular route).

2.2 Speed-Flow Diagrams

The speed-flow diagrams were drawn to verify the critical conditions, using the aggregated 5 min data for the adjacent points of the bottlenecks identified in section 2.1 above. Here the PCU conversion values are used for evaluation to eliminate influences by large vehicles (conversion factor of large vehicles to passenger vehicles is 1.5 (6)).

Figure 1 shows the speed-flow diagrams of Hakozaki rotary and Funaboribashi on ramp. Four points, including the bottleneck points are shown from upstream to downstream. The critical speed of the free-flow and congested-flow regions at the Hakozaki rotary and Funaboribashi on ramp are considered to be around 50km/h and 60km/h respectively, judging from the clearance of distribution in the speed-flow relationship.

The speed-flow diagrams are mainly classified into 4 patterns as follows: at the upstream the diagram shows a shape that resembles two bars which widen toward the ends, because the congestion extends from the bottleneck and traffic volume doesn’t reach the traffic capacity of this point. The diagram at just proximal upstream to the bottleneck shows a parabolic curve. At the bottleneck (or just proximal downstream to the bottleneck), a prolate elliptic cluster appears adjacent to the critical speed. In the downstream of the bottleneck, only data in the free-flow region exists, as the prolate elliptic cluster is absorbed into the high speed region. The patterns of the speed-flow relationship vary depending on the factors such as the road structure adjacent to the bottleneck. However, the diagrams at Hakozaki rotary show the 4 patterns prominently.

<table>
<tr><th>Relation to the bottleneck</th><th>Hakozaki rotary</th><th>Funaboribashi on ramp</th></tr>
<tr><td>Upstream</td><td>
440m upstream of Hakozaki rotary</td><td>
860m downstream of Funaboribashi on ramp</td></tr>
<tr><td>Proximal upstream</td><td>
220m upstream of Hakozaki rotary</td><td>
1,140m downstream of Funaboribashi on ramp</td></tr>
<tr><td>Bottleneck (proximal downstream)</td><td>
240m downstream of Hakozaki rotary</td><td>
1,420m downstream of Funaboribashi on ramp</td></tr>
<tr><td>Downstream</td><td>
500m downstream of Hakozaki rotary</td><td>
1,690m downstream of Funaboribashi on ramp</td></tr>
</table>

* Period for aggregation: 2004/10/1～2004/10/31

Figure 1: Speed-flow relationship

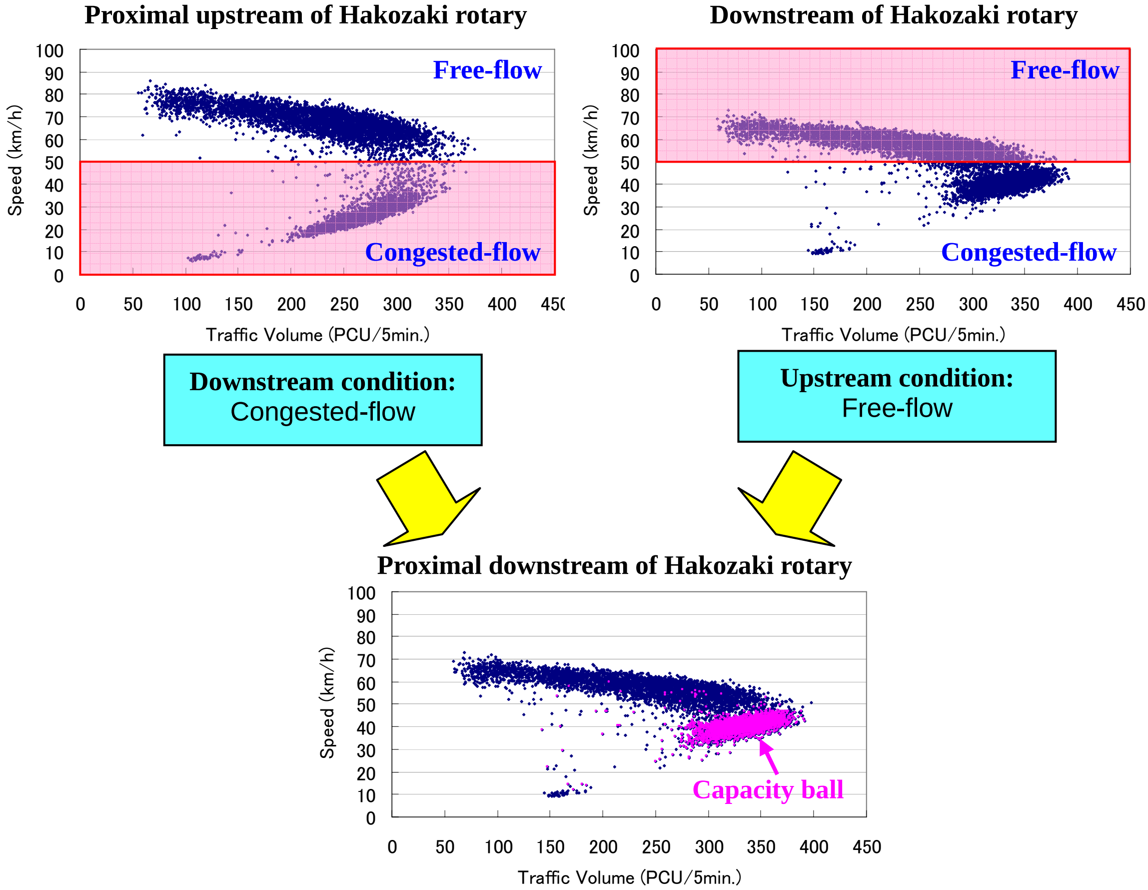
2.3 Method of Identification of Capacity Balls

The prolate elliptic cluster appearing at the bottleneck in section 2.2 above is considered to be a critical state. It appears when the proximal upstream of the bottleneck is congested-flow and the proximal downstream of the bottleneck is free-flow, and the bottleneck capacity will fluctuate greatly.

The data that meets these conditions, i.e. the distributed cluster of the critical state in the speed-flow relationship was named "capacity ball" and identified as shown in Figure 2.

The capacity balls identified excluding unusual data (with the speed of outside of the critical speed +/- 15km/h) are shown in Figure 3. The fluctuation of traffic volume in the capacity ball extends from 280 to 380 PCU/ 5 min at Hakozaki rotary and from 250 to 350 PCU/ 5 min at Funaboribashi

on ramp.
In these cases the bottleneck points aren't the merging points, but at the points in the downstream area. This has also been demonstrated by the analysis of the congestion mechanism with the use of the time-space diagram (7)(8).



* Critical speed: approximately 50km/h
Congestion determination speed for information provision on the traffic control system: 24km/h

Figure 2: Method of identification of capacity balls

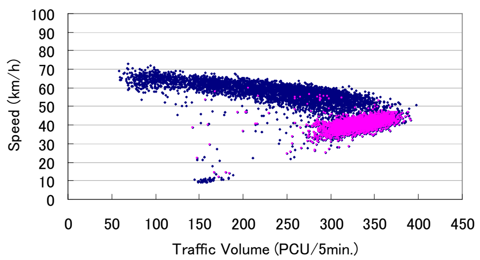
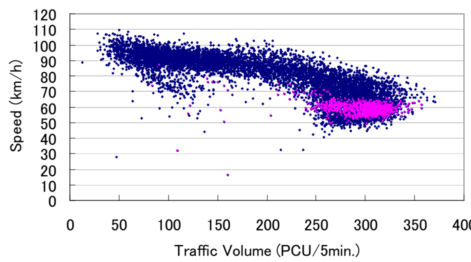
Hakozaki rotary	Funaboribashi on ramp
	
240m downstream of Hakozaki rotary	1,420m downstream of Funaboribashi on ramp

Figure 3: Capacity balls

3. ANALYSIS OF CAPACITY BALL

3.1 Analysis of Fluctuation Cluster of Capacity Balls by Dynamic Condition

Among the dynamic factors other than the road structure which have influences on the traffic capacity, we selected rainfall, days of the week (weekdays, Saturday or Sunday and holidays), and time of the day (daytime or nighttime) in order to analyze the capacity balls identified at Hakozaki rotary and Funaboribashi on ramp. The standard capacity balls were obtained from the data during daytime hours (from the sunrise time + 1 hour to the sunset time – 1 hour) on weekdays from October 1 and October 31, 2004 with no rainfall. The capacity balls influenced by the prescribed dynamic factors are compared with these standard capacity balls.

3.2 Influence of Rainfall

From the capacity balls identified in section 2.3, capacity balls during daytime hours on weekdays were classified by rainfall level and were studied based on influences by rainfall. The relationships between traffic volume/speed and rainfall level at Hakozaki rotary and Funaboribashi on ramp are shown in Figure 4. The relationship between the 5 min traffic volume and rainfall level shows the similar trend at both Hakozaki rotary and Funaboribashi on ramp, in that the traffic decreases remarkably with rainfall of 0 to 1 mm/h, however, it does not change with more rainfall.

The relationship between the speed and rainfall level, on the other hand, shows different trends at Hakozaki rotary and Funaboribashi on ramp. The speed at Hakozaki rotary decreases drastically with rainfall of 0 to 1 mm and does not change with more rainfall. However, at Funaboribashi on ramp, the speed increases with rainfall. This might be the results of influences by the road structure and difference in traffic flow itself.

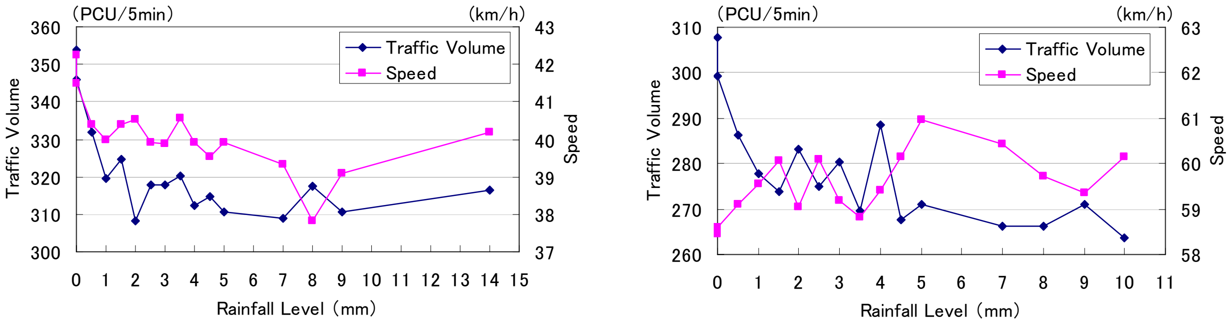


Figure 4: Relationship between traffic volume / speed and rainfall level (Hakozaki rotary (left) and Funaboribashi on ramp (right))

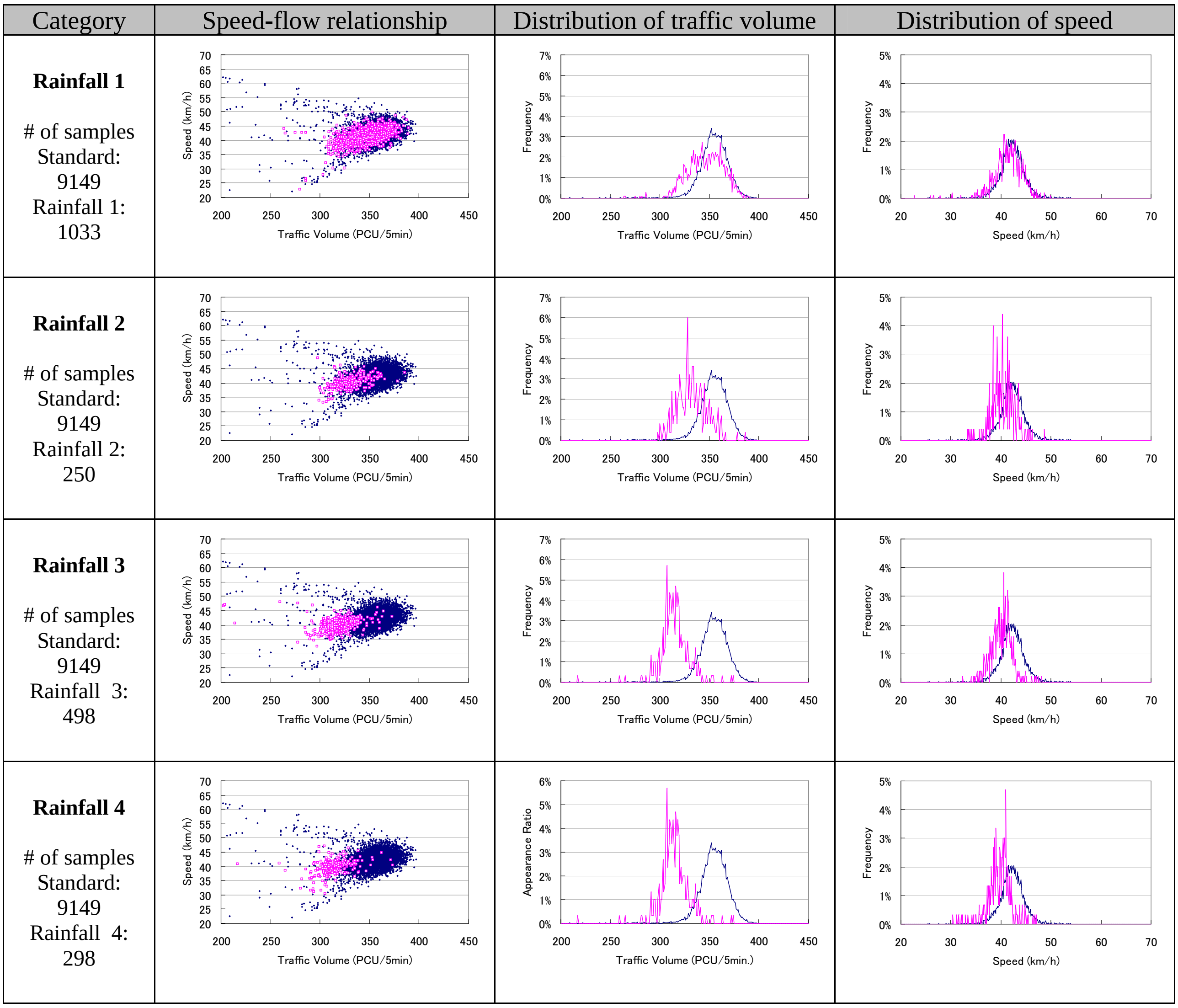
With these results, we determined that the capacity balls can be classified with rainfall levels. Here the capacity balls with rainfall are classified into 4 categories as shown in Table 1, and 5 capacity balls including the standard one (during daytime hours on weekdays without rainfall) are compared in order to study influence by rainfall.

Table 1: Categories of rainfall level

Name of capacity ball	Rainfall level
Standard	no rainfall
Rainfall 1	0.0 mm or more, and less than 0.5 mm
Rainfall 2	0.5 mm or more, and less than 1.0 mm
Rainfall 3	1.0 mm or more, and less than 3.0 mm
Rainfall 4	3.0 mm or more

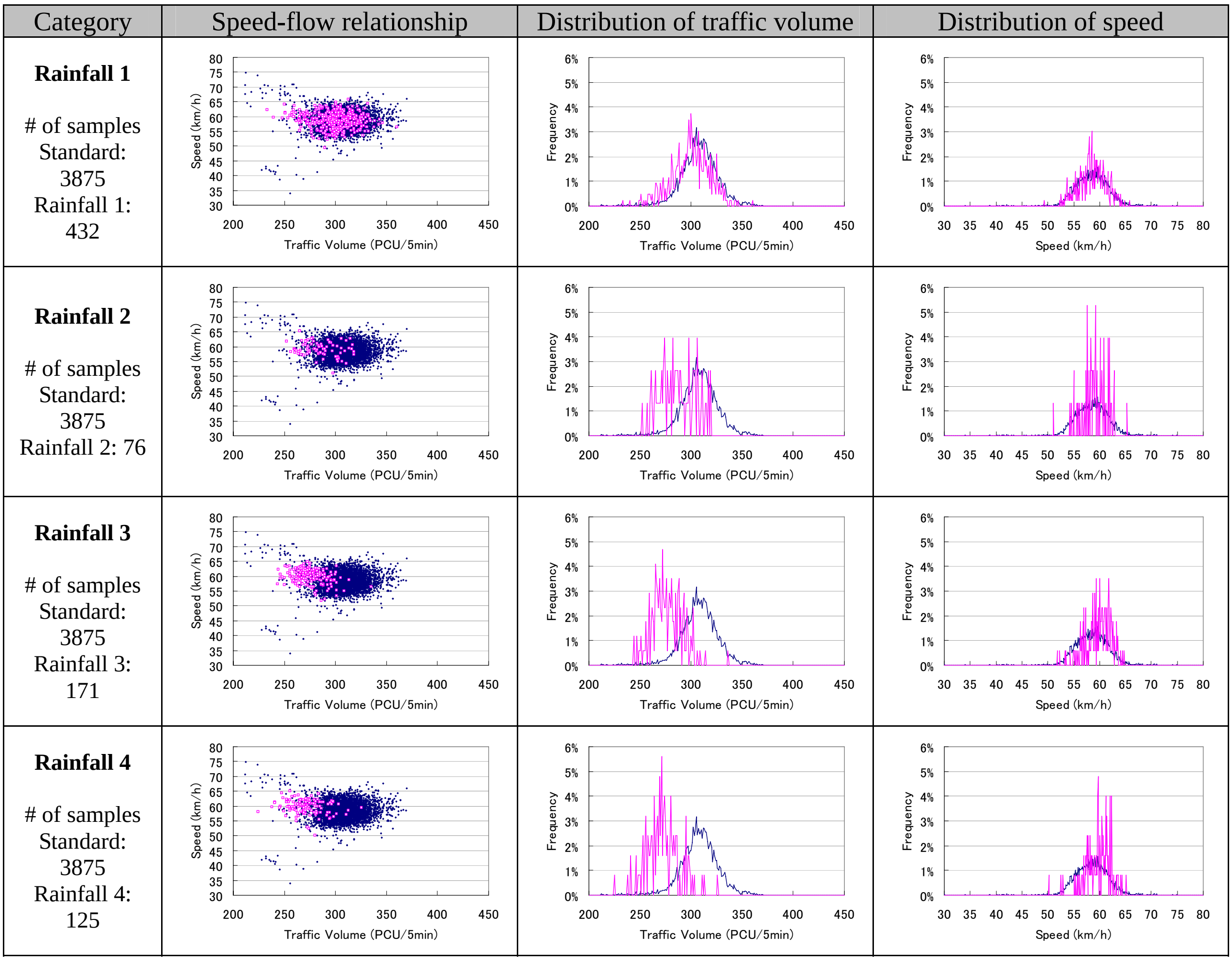
The speed-flow relationship, the distribution of the traffic volume and the distribution of the speed for the standard and rainfall capacity balls are compared in the Figure 5 and Figure 6. The position of the capacity ball for rainfall 1 in the speed-flow relationship is observed slightly to the left side. However, the positions of capacity ball for rainfall 2 to 4 are clearly different. The shapes of the distribution of the traffic volume for rainfall categories are obviously different. This shows that the traffic capacities are decreasing during rainfall.

The average data for the standard and rainfall capacity balls are compared in Table 2. As rainfall level increases, traffic capacity decreases in proportion, and the distance between two vehicles becomes longer. The reason for this could be that drivers tend to take longer distance between vehicles in the rainfall to for better safety.



* Legend: ◆ – Standard □ – Rainfall

Figure 5: Comparison with standard and rainfall capacity balls (Hakozaki rotary)



* Legend: ◆ – Standard □ – Rainfall

Figure 6: Comparison with standard and rainfall capacity balls (Funaboribashi on ramp)

Table 2: Influence by rainfall

	Hakozaki rotary					Funaboribashi on ramp				
	Std.	Rf. 1	Rf. 2	Rf. 3	Rf. 4	Std.	Rf. 1	Rf. 2	Rf. 3	Rf. 4
Traffic capacity (PCU/h)	353.8	345.8	332.1	319.1	314.5	307.7	299.2	286.3	276.1	271.9
Time headway (s/PCU)	1.70	1.73	1.81	1.88	1.91	1.95	2.01	2.10	2.17	2.21
Speed (km/h)	42.2	41.5	40.4	40.1	39.7	58.5	58.6	59.1	59.8	59.7
Space headway (m/PCU)	19.9	20.0	20.3	20.9	21.0	31.7	32.6	34.4	36.1	36.6

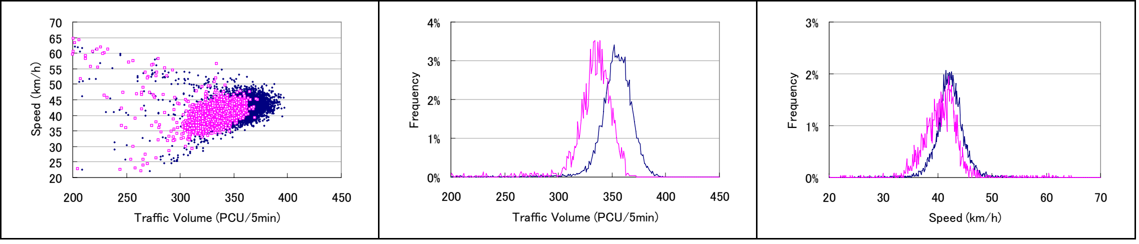
* Note: Std.; Standard, Rf.; Rainfall

3.3 Influence by Time of Day (Daytime and Nighttime)

From the capacity balls identified in section 2.3, capacity balls in the nighttime (on weekdays with no rainfall) are compared with the standard capacity balls (during daytime hours on weekdays with no rainfall) in order to study the influence of brightness.

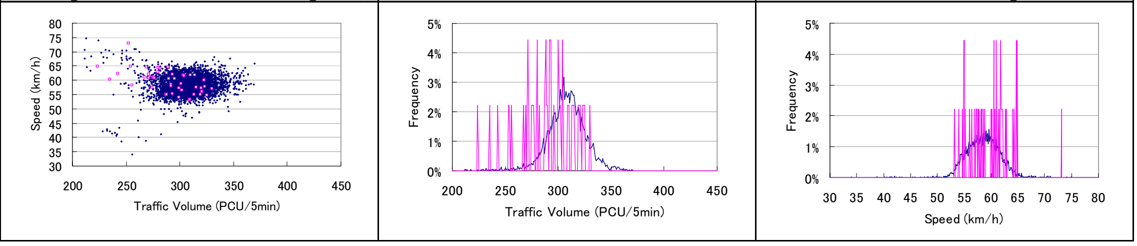
The speed-flow relationship, the distribution of the traffic volume, and the distribution of the speed for the standard and nighttime capacity balls are compared in Figure 7 and Figure 8. It is clearly observed in the speed-flow relationship that the position of a nighttime capacity ball is different from that of the standard one. The shape of distribution for nighttime is obviously different from that of daytime, thus showing that the traffic capacities are decreasing during nighttime hours.

The average data for the standard and nighttime capacity balls are compared in Table 3. During nighttime, traffic capacity decreases and the distance between two vehicles becomes longer. This may be because drivers tend to keep more distance between vehicles during nighttime hours than during daytime hours for safety reasons.

Category	Speed-flow relationship	Distribution of traffic volume	Distribution of speed
Nighttime # of samples Standard: 9149 Nighttime: 2245			

* Legend: ◆ – Standard □ – Nighttime

Figure 7: Comparison with standard and nighttime capacity balls (Hakozaki rotary)

Category	Speed-flow relationship	Distribution of traffic volume	Distribution of speed
Nighttime # of samples Standard: 3875 Nighttime: 45			

* Legend: ◆ – Standard □ – Nighttime

Figure 8: Comparison with standard and nighttime capacity balls (Funaboribashi on ramp)

Table 3: Influence by Daytime and Nighttime

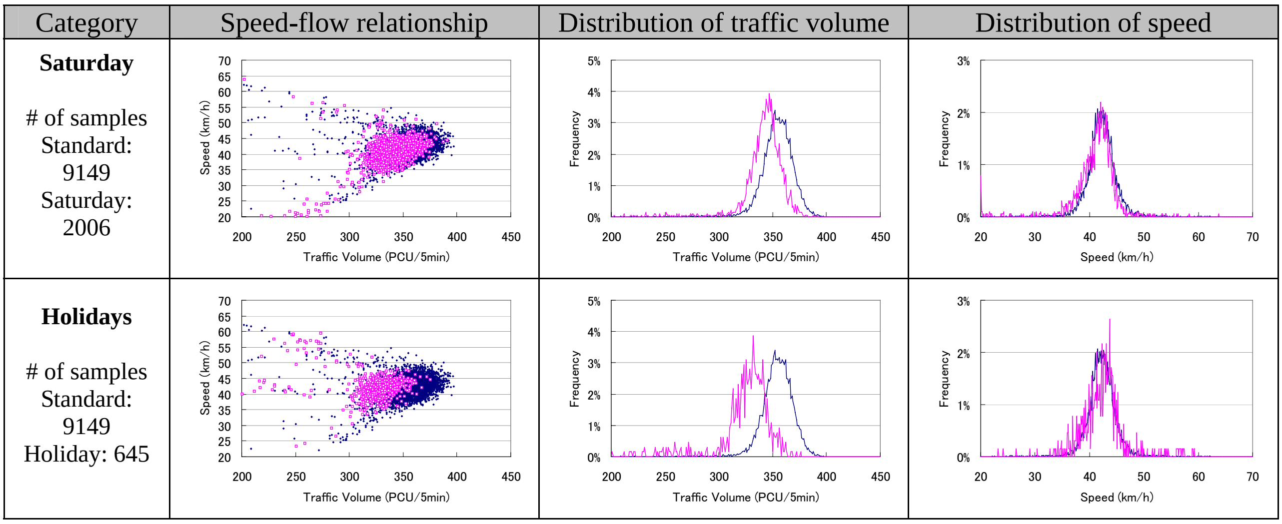
	Hakozaki Rotary		Funaboribashi on ramp	
	Standard	Nighttime	Standard	Nighttime
Traffic capacity (PCU/h)	353.8	332.9	307.7	289.3
Time headway (s/PCU)	1.70	1.80	1.95	2.07
Speed (km/h)	42.2	40.7	58.5	59.8
Space headway (m/PCU)	19.9	20.4	31.7	34.5

3.4 Influence by Day of Week (Weekday / Holiday)

From the capacity balls identified in section 2.3, Saturday capacity balls (during daytime hours on Saturdays with no rainfall) and holiday capacity balls (during daytime hours on holidays with no rainfall) are compared with the standard capacity balls (during daytime hours on weekdays with no rainfall) in order to study influence by day of the week.

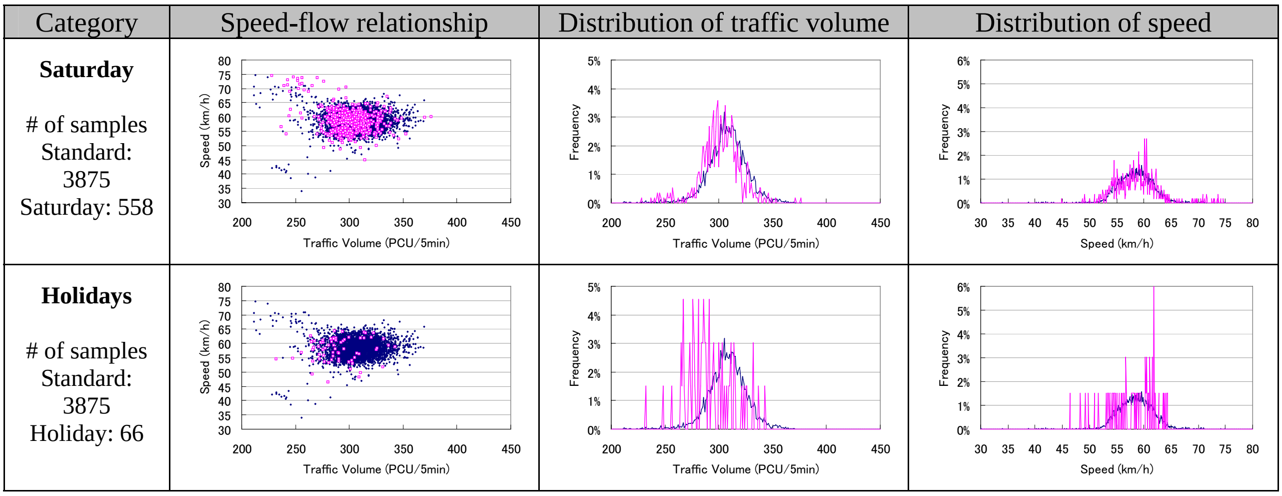
The speed-flow relationship, the distribution of the traffic volume and the distribution of the speed for the standard, Saturday and holiday capacity balls are compared in Figure 9 and Figure 10. The position of the Saturday capacity ball in the speed-flow relationship is observed to the left side, and that of holiday capacity ball is clearly different. The shapes of the distribution for Saturdays and holidays are obviously different from the criteria, thus showing that the traffic capacities are decreasing on Saturdays and holidays.

The average data for the standard, Saturday, and holiday capacity balls are compared in Table 4. On Saturdays and holidays, traffic capacity decreases and the distance between two vehicles becomes longer. This would be because so-called “Sunday drivers” who don’t drive daily may increase on holidays and many of them may drive with a longer distance between vehicles.



* Legend: ◆ – Standard □ – Saturday or Holidays

Figure 9: Comparison with standard, Saturday and holiday capacity balls (Hakozaki rotary)



* Legend: ◆ – Standard □ – Saturday or Holiday

Figure 10: Comparison with standard, Saturday and holiday capacity balls (Funaboribashi on ramp)

Table 4: Influence by day of the week

	Hakozaki rotary			Funaboribashi on ramp		
	Standard	Saturday	Holiday	Standard	Saturday	Holiday
Traffic capacity (PCU/h)	353.8	341.7	324.6	307.7	301.4	290.8
Time headway (s/PCU)	1.70	1.76	1.85	1.95	1.95	2.06
Speed (km/h)	42.2	41.0	42.4	58.5	58.5	57.7
Space headway (m/PCU)	19.9	20.0	21.8	31.7	31.7	33.1

3.5 Summary of Influences

Fluctuations of the average traffic capacity and the speed at Hakozaki rotary and Funaboribashi on ramp are listed in the Table 5. Among the influencing factors such as day, time or rainfall, rainfall is the largest among them. The traffic capacity also decreased by more than 11% in the capacity ball of the rainfall 4. The traffic capacity decreases by around 6% at night, 2% to 3% on Saturdays and around 5% to 8% on holidays. As for the speed, data at Hakozaki rotary shows a decreasing trend. On the contrary, data at Funaboribashi on ramp shows an increasing trend. We conclude this is because the drivers keep plenty of distance between vehicles as they increase their speed.

Table 5: Fluctuation of traffic capacity and speed

Category of capacity balls	Hakozaki rotary				Funaboribashi on ramp			
	Traffic capacity (PCU/5min)		Speed (km/h)		Traffic capacity (PCU/5min)		Speed (km/h)	
	Average	Ratio of reduction	Average	Ratio of reduction	Average	Ratio of reduction	Average	Ratio of reduction
Standard	353.8		42.2		307.7		58.5	
Rainfall 1	345.8	2.3%	41.5	1.8%	299.2	2.7%	58.6	-0.2%
Rainfall 2	332.1	6.2%	40.4	4.4%	286.3	6.9%	59.1	-1.1%
Rainfall 3	319.1	9.8%	40.1	5.0%	276.1	10.2%	59.8	-2.4%
Rainfall 4	314.5	11.1%	39.7	6.0%	271.9	11.6%	59.7	-2.1%
Nighttime	332.9	5.9%	40.7	3.7%	289.3	6.0%	59.8	-2.4%
Saturday	341.7	3.4%	41.0	3.0%	301.4	2.0%	58.7	-0.4%
Holiday	324.6	8.3%	42.4	-0.4%	290.8	5.5%	57.7	1.2%

4. CONCLUSION AND FUTURE TASKS

It was verified by identifying the capacity balls that the bottleneck capacity fluctuates remarkably in response to various factors. Therefore it is not appropriate to determine the bottleneck capacity values only from the envelope curve of the speed-flow relationships without stratifying the observed data by fluctuation factors such as rainfall, time of the day or day of the week.

The measures to expand capacity have traditionally been taken mostly for the merging points themselves, decided from the congestion determination speed for information provision. However, it is preferable that the capacity expansion measures should be taken toward the true bottlenecks which were determined to be at the downstream side of the merging points in this study.

The fluctuation of the traffic capacity by influential factors showed approximately the similar trend at Hakozaki rotary and Funaboribashi on ramp. However, the fluctuations of the speed were different for the two points. This is because that the shape of the speed-flow relationship itself is different which is presumed by the influence of the road structure and other factors. The cause of these differences may be seen by analysis of the congestion mechanism for Funaboribashi on ramp as well as Hakozaki rotary already analyzed (7)(8). The location displacement, whatever the fluctuations of the traffic capacity at other bottlenecks, shows a similar trend should be verified.

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