A STUDY ON TRAFFIC CAPACITY AT THE EXPRESSWAY TOLLGATE IN THE CONTEXT OF AUTOMATIC PAYMENT TRANSACTION WITHOUT STOPPING

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Abstract: A system of automatic payment transaction without stopping at the expressway tollgate is called the ETC system in Japan, and it is operated as Mixture Lane under the low rate of ETC users. In the study, non-ETC vehicle and ETC vehicle, starting delay of following vehicle according to passing ETC vehicle is considered, the estimating method of traffic capacity according to weighted average of processing time is proposed and inspected under the high rate of ETC users.

Key Words: Electronic Toll Collection (hereinafter ETC) System, Traffic capacity at the expressway tollgate

1. INTRODUCTION

A system of automatic payment transaction without stopping at the expressway tollgate is called the ETC system in Japan. The new system is based on the mechanism of exchanging radio signals between the on-board equipment and the antenna at the tollgate, storing data in it and calculating the toll at the tollgate. Therefore, ETC users are able to pass the tollgate without stopping and settle the toll later. As compared with similar systems that have already been achieved in the other countries, the chief characteristic points of the ETC system are that the applications are abundant and "Kilometrage System" which the toll is calculated according to kilometrage is adopted for the toll collection.

Introduction of the ETC system is much expected to improve drivers' benefit and convenience by untying traffic congestion. However, the cost, which the on-board equipment of the ETC system is installed in the vehicle, is relatively expensive, about 300 US dollars, because it was devised with an aim to make the multifunction in Japan. Therefore, it may take long time to install the equipment, and traffic congestion will be deteriorated when some of lanes are operated as the lanes of using for only ETC users (hereinafter Exclusive Lane for ETC) under the low rate of ETC users. After some examinations how to operate the tollgate lane under the mixed condition of vehicles with and without the equipment, the said lane is operated as follows: both type of users (ETC user and non-ETC user) are able to pass simultaneously a lane (hereinafter Mixture Lane) under the low rate of ETC users.

In the paper, the vehicle behavior of ETC users and non-ETC users at the tollgate is postulated, and the method of estimating traffic capacity in the Mixture Lane is proposed. Then some interesting conclusion is obtained by comparing the field measurements with that of estimation regarding traffic capacity in the Mixture Lane.

2. PRESENT SITUATION OF TRAFFIC CONGESTION

Traffic congestion on interurban expressway in Japan is defined as “the situation that each vehicle is made to drive at low speed below 40 kilometers per hour in the way of a kilometer or more, the said situation continues over 15 minutes”

As for the occurrence frequency of traffic congestion on interurban expressway, it had a tendency to go from bad to worse year-by-year in the 1990s. It has been decreasing in the 2000s because measures against traffic congestion were carried out on a large scale and Japan has been languid economy in recent years. But the number of it is no fewer than 28,000 times per a year (Figure-1).

This congestion may be divided into 1)“congestion by traffic centralization” – it occurs because traffic volume over flow traffic capacity centralizes at a bottleneck, 2)“construction congestion” – it occurs because the number of lanes is decreased by construction regulation, 3)“traffic accident congestion” – it occurs because the number of lanes is decreased by traffic accident regulation.
The occurrence frequency of congestion by traffic centralization is the most and occupies 70% of total.

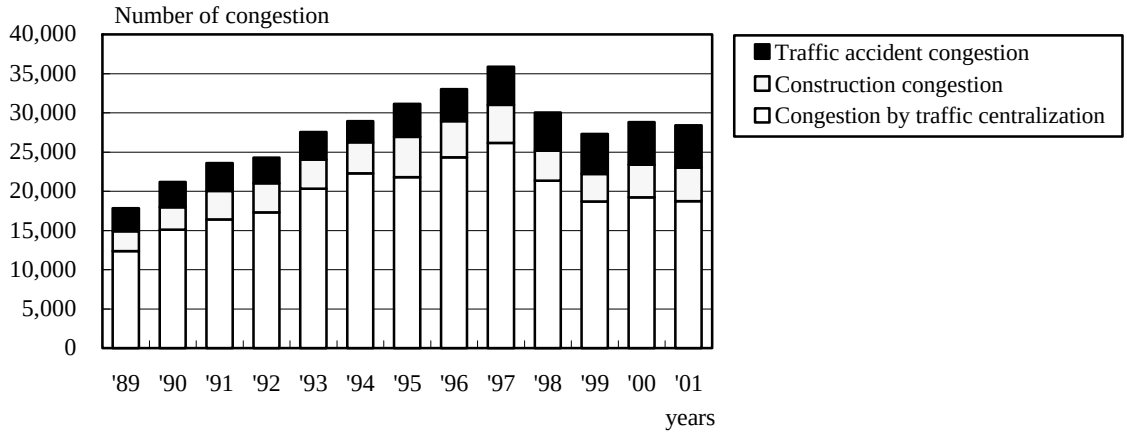


Figure-1 Occurrence frequency of traffic congestion on interurban expressway

Further, as for the factors in congestion by traffic centralization according to the difference of bottleneck structure, the rate of the congestion at the tollgate is 30% of total, and the ETC system is much expected to solve it (Figure-2).

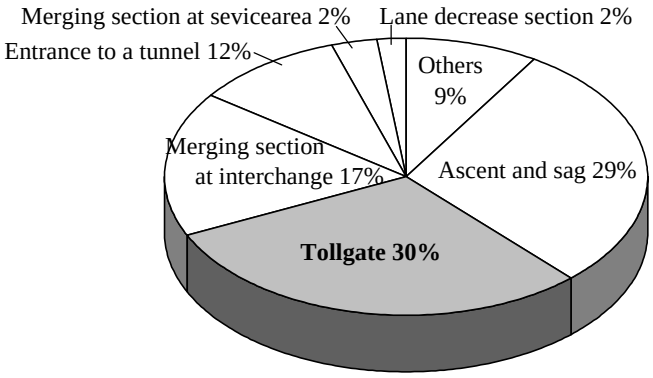


Figure-2 Rate of congestion by traffic centralization according to the difference of bottleneck structure

3. DATA FOR ANALYSIS

3.1 TOLLGATES AND DATES FOR ANALYSIS

The tollgates and dates for the analysis of traffic capacity at Mixture Lane are indicated in Table-1. In making the analysis of processing time, it is necessary to extract the tollgates that are operated as Mixture Lane and make queues. Therefore, the study took the operational situation of Mixture Lane and the situation that the queue was frequently occurred into consideration, and extracted them.

As to the dates for analysis, in order to extract as many vehicles of ETC users (hereinafter ETC vehicles) as possible, the study selected the dates when Mixture Lane was operated and time had adequately gone by from full-scale introduction of the ETC system (on November 30, 2001). And the exit of Kilometrage System and the entrance of Flat Rate System are selected each other as covered tollgates.

Here, Kilometrage System is the method that a magnetic card is ticketed at the entrance on the expressway and presented to a toll taker at the exit, and the toll according to kilometrage is paid. It is mainly adopted in the interurban expressway. On the other hand, Flat Rate System is the method that fixed toll according to type of vehicle is paid at the entrance on the expressway, it is mainly adopted in urban expressway.

Table-1 Tollgate and date for analysis

Toll collection form	Route name	Tollgate name	Date for analysis
Exit of Kilometrage System	Higashi-Kanto Expressway	Narita (exit)	THU 14/02/2002 - THU 20/02/2002 For 7 days
Flat Rate System	Keiyo Expressway	Funabashi	

3.2 DATA FOR ANALYSIS

In order to estimate traffic capacity under the situation operated Mixture Lane, the study focused attention on S4 by traffic detector data as shown in Figure-3, and measured processing time by the difference time between passing time of each vehicle.

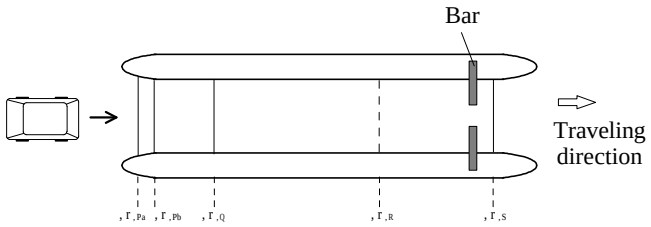


Figure-3 Position of traffic detector

Furthermore, the data for analysis has to be extracted from the situation which queues are frequently formed. But because the situation is not made a judgment on directly, in consideration of the time difference between passing time through S_4 of leading vehicle (which is coming out tollgate) and passing time through S_{1a} of following vehicle (which is

coming in tollgate), it is judged as follows.

Situation of a formed queue
: Passing time through S_4 of leading vehicle >
passing time through S_{1a} of following vehicle

* Following vehicle is passing through S_{1a}
before leading vehicle passes through S_4

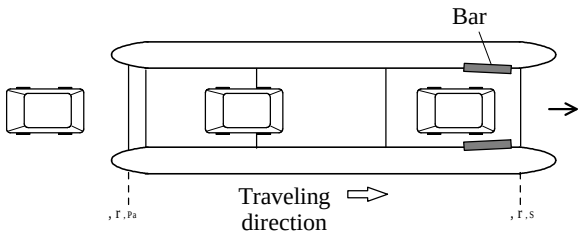


Figure-4 Conception of a judgment of a formed queue

3.3 THE NUMBER OF SAMPLES

The number of processing time samples by pairing of leading vehicle and following vehicle (ETC vehicle and non-ETC vehicle) for analysis of the study is indicated in Table-2. Altogether, many samples were extracted for analysis.

Table-2 Number of processing time samples for analysis

Toll collection form	Tollgate name	The total number of samples	Paring of following vehicles		
			Leading vehicle	Following vehicle	The number of samples
Exit of Kilometrage System	Narita (exit)	1,473	Non-ETC	Non-ETC	1,169
				ETC	202
			ETC	Non-ETC	70
				ETC	32
Flat Rate System	Funabashi	41,693	Non-ETC	Non-ETC	40,417
				ETC	692
			ETC	Non-ETC	521
				ETC	63

4. ESTIMATING OF TRAFFIC CAPACITY BY PROCESSING TIME

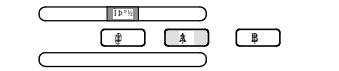
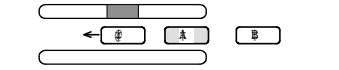
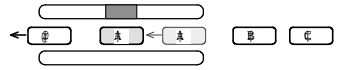
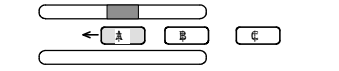
4.1 CONCEPTION OF PROCESSING TIME

Heretofore, as the top Figure-5 indicates, every vehicle was brought to a stop at the side of tollgate booth, and the toll was paid. In consequence, processing time at general lane was measured as time difference of each vehicle arriving or starting there.
However, because ETC users don't stop there, the conception of processing time need to be defined. Therefore as shown in the bottom Figure-5, the study defines processing time of ETC vehicles as time difference between the time that the leading vehicle starts from the side of tollgate booth and the time that the interested ETC vehicle passes there.

Furthermore, in the situation that Mixture Lane is operated, driver's distinction and decision of leading vehicle (the driver of interested vehicle can't determine whether the leading vehicle is ETC vehicle or non-ETC vehicle) have to be considered. And it is presumed that "the leading vehicle, which includes of ETC vehicle and non-ETC vehicle, is assumed non-ETC vehicle in the situation that Mixture Lane is operated, and the interested vehicle behaves with the premise that the leading vehicle would stop." Thus if leading vehicle is ETC vehicle and pass the tollgate without stopping, it is possible that following vehicle has starting delay.

Therefore, the study analyzes, at Figure-5, focusing on processing time of following vehicles according to ETC vehicles passing the tollgate.

The case of general lane

Time flow	Schema	Overview
processing time of the vehicle 2		The vehicle 1 stops at the side of tollgate booth, and the toll is paid.
		The user of vehicle 1 finishes paying and starts. Then processing time of the vehicle 2 is measured.
		The vehicle 1 moves on, and the the vehicle 2 stops at the side of tollgate booth, and the toll is paid.
		The user of vehicle 2 finishes paying and starts. Then the processing time measurement of the vehicle 2 finished. Then processing time of the vehicle 3 is measured.

The case of Mixture lane

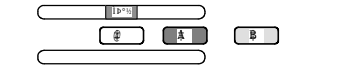
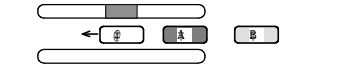
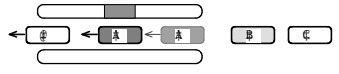
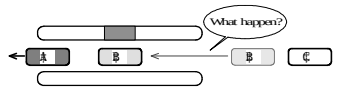
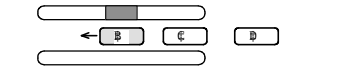
Time flow	Schema	Overview
processing time of the ETC vehicle 2 processing time of the vehicle 3		The vehicle 1 stops at the side of tollgate booth, and the toll is paid.
		The user of vehicle 1 finishes paying and starts. Then processing time of the ETC vehicle 2 is measured.
		The ETC vehicle 2 passes through the side of tollgate booth Then the processing time measurement of the ETC vehicle 2 finished. Then processing time of the vehicle 3 is measured.
		The vehicle 3 moves on, and the toll is paid (in case of non-ETC vhehicle).
		The user of vehicle 3 finishes paying and starts. Then the processing time measurement of the ETC vehicle 3 finished. Then processing time of the vehicle 4 is measured.

Figure-5 Conception of processing time in the situation that Mixture Lane is operated

4.2 EXPRESSION OF ESTIMATING OF TRAFFIC CAPACITY

In consideration of effects on processing time of following vehicle from passing of ETC vehicle, in case that leading vehicle is ETC vehicle, whereas it is non-ETC vehicle, starting delay of following vehicle is presumed as follows.

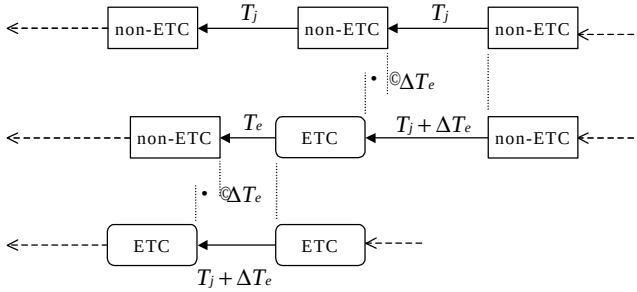


Figure-6 Effect on processing time of following vehicle from passing of ETC vehicle

On the assumption of Figure-6, the study defines that traffic capacity of Mixture Lane is estimated as traffic capacity by weighted average between processing time of ETC vehicle and non-ETC vehicle.

$$Q_e = 3{,}600/\overline{T} \quad (vehicles/h * a\ lane)$$
$$\overline{T} = (T_e + \Delta T_e) * r_e/100 + T_j * (1 - r_e/100) \quad (\text{sec}onds)$$

Where;

r_e : Rate of ETC vehicles in Mixture Lane
T_e : Processing time of ETC vehicle
T_j : Processing time of each non-ETC vehicle
ΔT_e : Effect on processing time of following vehicle from passing of ETC vehicle

4.3 RESULT OF PROCESSING TIME ANALYSIS

The result of analysis of processing time at two covered tollgates in the study is shown in Figure-7 and Table-3.

Both Narita and Funabashi tollgates, starting delay of non-ETC vehicle following ETC vehicle is observed, it is 1.2 – 1.3 second (average value) longer in comparison to between each non-ETC vehicle.

Correspondingly, ETC vehicle following ETC vehicle have only a few starting delay, it is 0.1 – 0.3 second (average value) in comparison to the case of ETC vehicle following non-ETC vehicles.

Thus, the study accounts that ETC vehicle following ETC vehicle have no starting delay, and considers starting delay only in case of that following vehicle is non-ETC vehicle.

Table-3 Result of analysis of processing time

Toll collection form	Tollgate name	Paring of following vehicles		The number of samples	Result of aggregated processing time (second)				
		Leading vehicle	Following vehicle		Average	15% tailing	50% tailing	85% tailing	Standard deviation
Exit of Kilometrage System	Narita (exit)	Non-ETC	Non-ETC	1,169	13.7	11.5	13.5	16.1	2.4
			ETC	202	3.2	1.9	2.8	4.3	1.5
		ETC	Non-ETC	70	14.9	12.9	14.7	17.3	2.1
			ETC	32	3.3	2.1	3.1	4.4	1.2
Flat Rate System	Funabashi	Non-ETC	Non-ETC	40,417	8.0	4.5	7.1	11.7	3.6
			ETC	692	2.8	1.6	2.5	3.8	1.6
		ETC	Non-ETC	521	9.3	5.6	8.7	13.0	3.8
			ETC	63	3.1	2.1	2.8	4.2	1.2

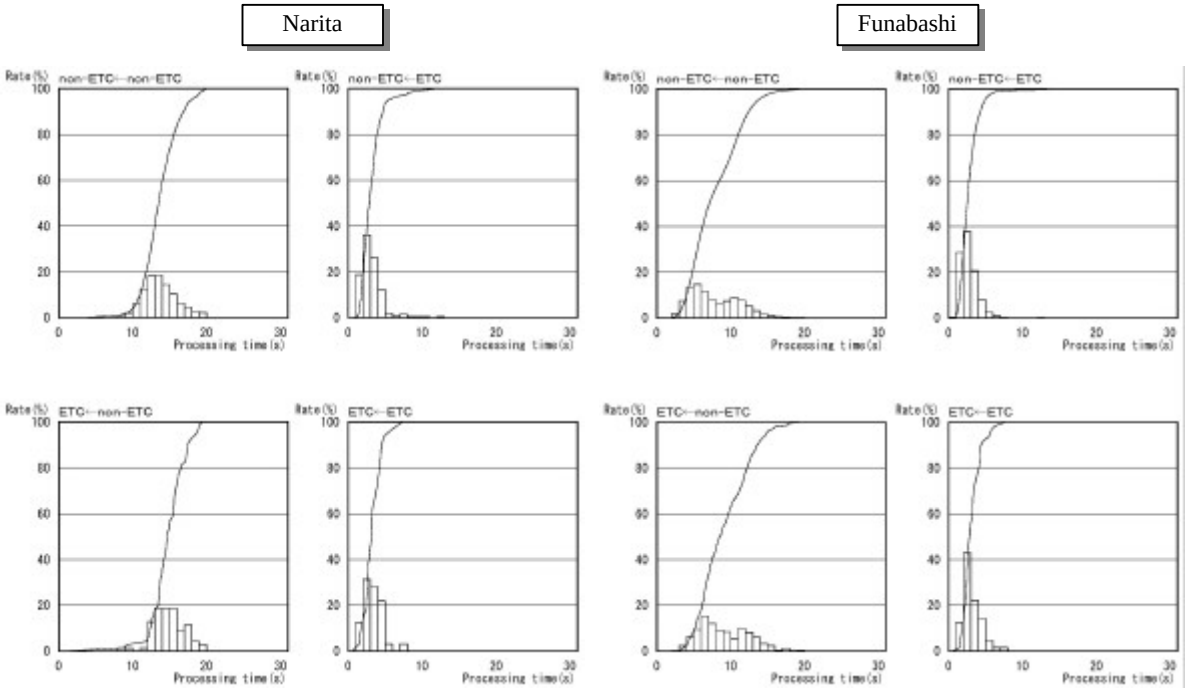


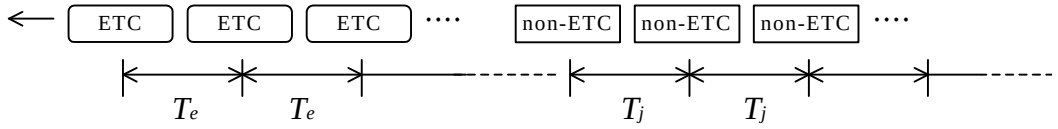
Figure-7 Result of analysis of processing time

From the result of it, according to following situation whether ETC vehicle or non-ETC vehicle, average of processing time is different value. Therefore, the scope that average of processing time appeared can be summarized as follows.

Upper limit

Upper limit is the case of the most efficient processing. It is the case that ETC vehicle and non-ETC vehicle is utterly compartmentalized and pass.
Average of processing time

$$\overline{T} = T_e * r_e/100 + T_j(1 - r_e/100)$$



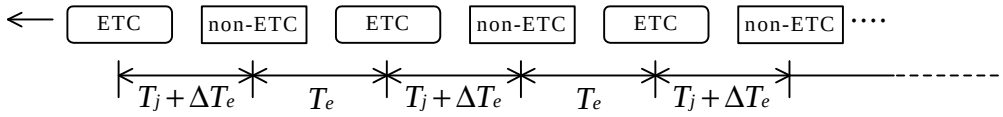
Lower limit

On the other hand, lower limit is the case of the most inefficient processing. It is the case that ETC vehicle and non-ETC vehicle is alternately passing. The case is categorized into the case that the rate of ETC vehicles (r_e) is under 50% and over 50%.

$r_e \leq 50\%$

Average of processing time

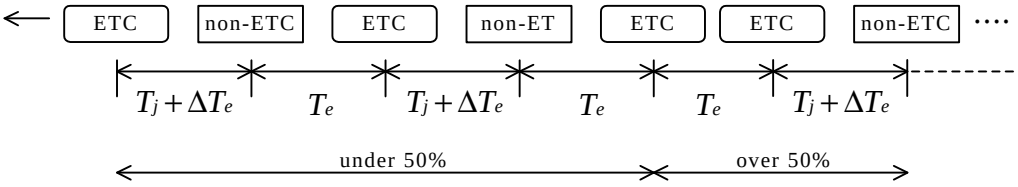
$$\overline{T} = (T_e + \Delta T_e) * r_e/100 + T_j(1 - r_e/100)$$



$r_e \geq 50\%$

Average of processing time

$$\overline{T} = T_e * r_e/100 + (T_j + \Delta T_e)(1 - r_e/100)$$



4.4 RESULT OF TRAFFIC CAPACITY ANALYSIS

As the result of above, average of processing time that is estimated by using weighted average of processing time of ETC vehicle and non-ETC vehicle by the rates of ETC vehicle is shown in Figure-8.

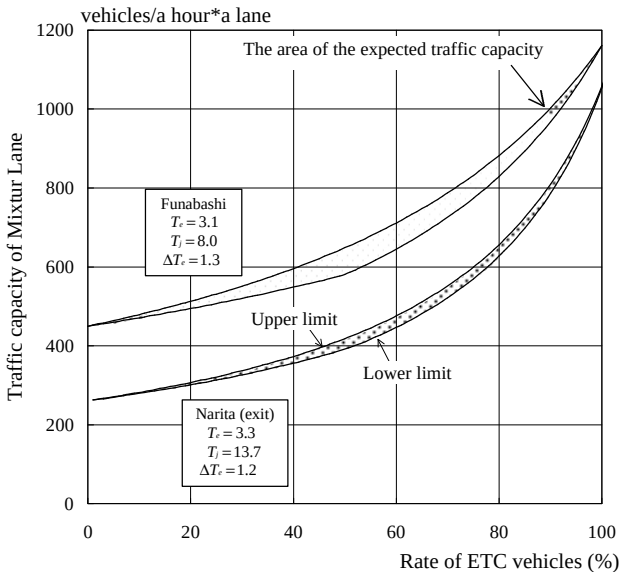


Figure-8 Estimating result of traffic capacity of Mixture Lane

5. VERIFICATION BY ACTUAL RESULT

5.1 SAMPLING METHOD

The rate of ETC vehicle in Mixture Lane is not large. Therefore if traffic capacity in Mixture Lane is estimated by the unit time such as for 15 minutes or an hour, the rate of ETC vehicles is a few percentages.
Then, as sampling method replicated the situation of the high rate of ETC vehicles, the study aggregates the processing time by the unit number and does flow rate conversion to a vehicle per an hour.
The estimating method of traffic capacity according to the rate of ETC vehicles by using ETC system data is as follows.

Traffic capacity (vehicle / a hour) = aggregated unit number (vehicles)
* 3,600 (seconds) / processing time per aggregated unit number (seconds)

The rate of ETC vehicles (%)
= The number of ETC vehicle / aggregated unit number * 100

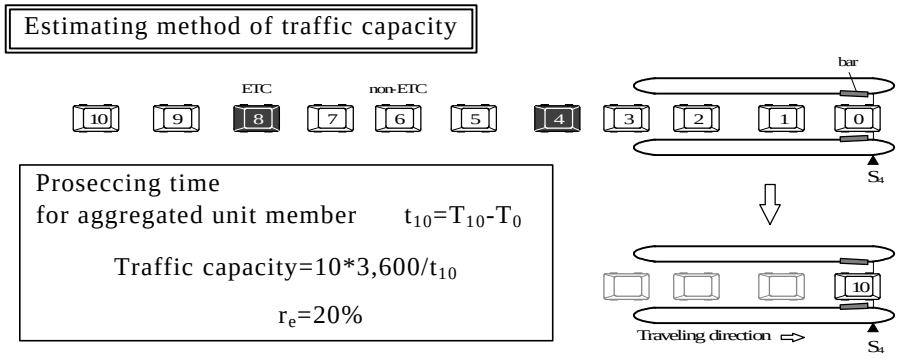


Figure-9 Conception of estimating of traffic capacity by the rate of ETC vehicles

Alteration of aggregated unit number in above expression give the result of various rate of ETC vehicles. For example, the unit number is a few sampling, the situation of the high rate of ETC vehicles in Mixture Lane is reproduced.
However, in case of method, because individual attribute per a using vehicle have a great influence, it is considered that data accuracy is little worse.

5.2 RESULT OF COMPARISON VERIFICATION

Expression related the rate of ETC vehicles and traffic capacity that is estimated by actual processing number, and expression of estimating of traffic capacity that is estimated by average of processing time are shown in Figure-10.
In the study, non-ETC vehicle and ETC vehicle, starting delay of following vehicle according to passing ETC vehicle is considered, the estimating method of traffic capacity according to weighted average of processing time is proposed. The result of comparison from actual processing number, it could be recognized that it can be reproduced in high accuracy.

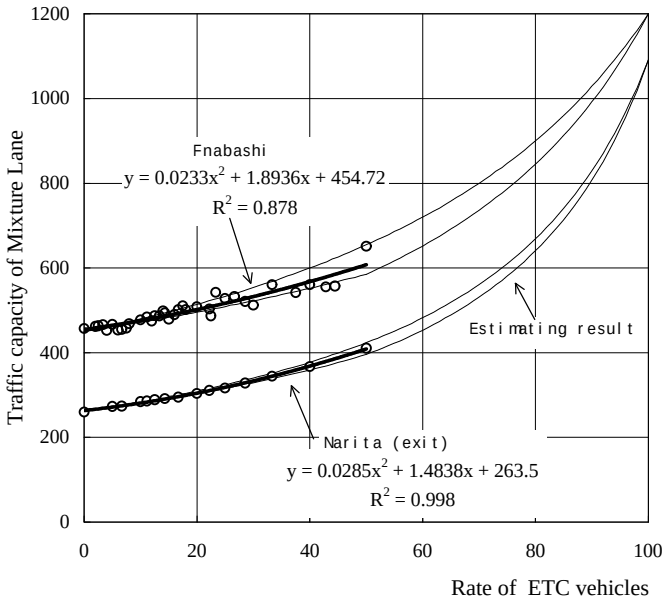


Figure-10 Analysis result of traffic capacity by the rate of ETC vehicles

6. CONCLUSION

In the study, under the low rate of ETC users, the method of estimating of traffic capacity in Mixture Lane is proposed and inspected under the high rate of ETC users. And a hereafter direction of operation of Mixture Lane can be shown.

At the same time, traffic capacity in the situation that the rate of ETC vehicles is 100% is produced. But as for it, occur rate of mistaken intrusion (the case is non-ETC vehicle intrude in Exclusive Lane for ETC by mistake) and system error are considered, and safety side operation is needed.

And traffic capacity by the rate of ETC vehicles is greatly influenced by using attribute of each tollgate. For example, processing time will be totally long in the tollgate that the rate of truck is large and in the local tollgate that is strong sightseeing attribute and change is given by using highest bill. Consequently, after consideration the using attribute, parameter for considering the lane operation is considered.

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