Development of the Status Map for Integration of Ramp Metering and Information Provision

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Abstract: On urban expressways, ramp metering and information provision conducted by road administrators have significant effects on mitigating traffic delay. Although these two methods are already in service, they are operated independently. To combine these beneficial methods, this paper aims to develop “Status Map” which is based on the analysis of queuing pattern on the traffic network. Simulation on radial road section consists of paralleled urban expressway and arterial shows that significant relationship exists between Status Map and delay calculated on dynamic simulator, which implies that Status Map as a static framework would still be applicable to future traffic control method.

Keywords: *traffic control, ramp metering, information provision, bottleneck capacity*

1. INTRODUCTION

Ramp metering and information provision are the major approaches to influence the route choice behavior of travelers in order to improve traffic congestion. As the ramp metering method, Sasaki and Myojin (1968) proposed the method to estimate traffic flow for each OD pair and proposed ramp metering method with Linear Optimization problem. Papageorgiou *et al* (1991) proposed the local feedback ramp metering method called ALINEA and field experiment taken in Paris, France and Amsterdam, Netherland showed the efficiency of ALINEA ramp metering. Yoshii *et al* (2008) proposed the area metering method called MFD (Macroscopic Fundamental Diagram) ramp metering based on what mentioned in Nikolas and Daganzo (2007), and revealed the effectiveness of this control method on SOUND macroscopic simulator.

As the evaluation of the effect of information provision, Arnott *et al* (1991) claimed that information provision is beneficial for individual drivers and have an influence on user’s route choice but, on the other hand, there are so many cases which raise the overall travel cost on the network when individuals are fully informed. Oguchi *et al* (1997) revealed the relationship between congestion length information provided by VMS and user’s route choice behavior on which parallel two independent links exists to seek the proper way to provide information avoiding delay caused by information provision, as in Arnott *et al* (1991). Information provision is not applied for the method of traffic flow management intensively but it has an effect on drivers’ route choice and traffic congestion.

These two methods to manage traffic flow are both effective and already practiced in the real traffic. However, they have been developed independently, and it may not be always effective if they are just simply combined. In order to examine the effectiveness of the

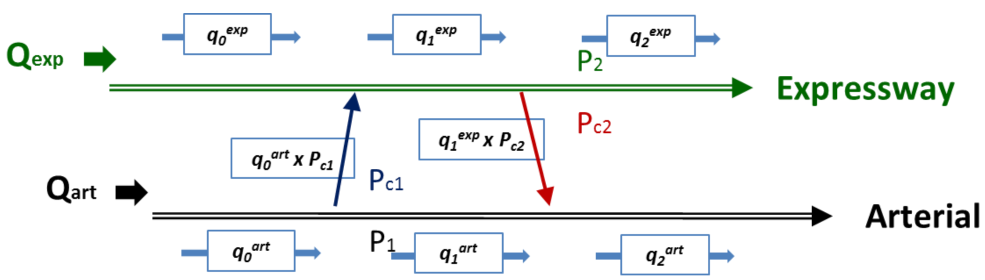

Fig.1 Hypothetical network consists of parallel expressway and arterial
(All q_i in this figure denotes the traffic flow at each subsection i)

combined method, it seems necessary to study a methodology discussing ramp metering with information provision.

This research aims to develop a static model scheme considering ramp metering and information provision and to acquire the knowledge whether the static model gives any useful information for traffic control or not. This study develops "Status Map" which represents static queuing patterns on a network.

Contents of this paper are shown below. Section 2 defines the concept of Status as the main topic of this paper to show how to acquire Status itself, the method to visualize: Status Map and how to apply Status Map for traffic management. Section 3 describes the validation of the Status Map by using a hypothetical data set. The calculation results from the static model and CTM (Cell Transmission Model) as a dynamic representation are compared. In closing, Section 4 discusses the results and shows the direction of future work.

2. STATUS MAP

Delay of the vehicles is mainly caused by queues on the road link. When the capacities of the bottlenecks are not sufficient to the travel demands, delays are caused by the queues even if the ramp metering and information provision are successfully performed. The length of the queue caused by the bottleneck seems to be main factors of the delay of individual travelers. However, road sections influenced by such queues depend on places of the bottlenecks where queues are generated. This study proposes "Status Map" that describes places of head of the queues in order to specify the influence of the ramp metering and information provision. "Status Map" is described in the typical hypothetical expressway network consists of paralleled expressway and arterial road, an on-ramp and an off-ramp as shown in **Fig.1**.

2.1 Basic Concepts

In this research, we define "Status" as a static representation of the queues on the network calculated from the amount of input flow and turning percentage inside the network. This concept is proposed to estimate the queue from each bottleneck on the network.

To deal with such queue on the traffic network, it is true that dynamic traffic analysis such as *feed-forward analysis* is the most appropriate way, however, reproduction on dynamic simulator is quite difficult and it often requires too much time. Static analysis, on the other hand, may not provide optimum solution, however, it might provide an intuitive solution without complex and time-consuming calculation. This research aims to acquire the knowledge on the relationship between this static Status and the result of dynamic analysis to evaluate the potential of this static method when applied for future traffic management method.

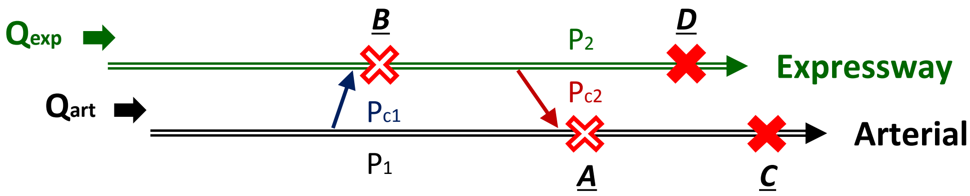

Fig.2 Potential source of the queues

2.2 Definition of the Status

On the network shown in **Fig.1**, assuming that four values $(P_1, P_2, Q_{exp}, Q_{art})$ are given and fixed for a time interval. Traffic flows for each subsection is determined statically by calculating the set of **Eq(1)-(6)**. Here, q_i^{exp} and q_i^{art} denotes traffic volume of subsection $i(i = 0,1,2,\cdots)$ for expressway and arterial street, respectively.

$$q_0^{exp} = Q_{exp} \tag{1}$$
$$q_0^{art} = Q_{art} \tag{2}$$
$$q_1^{exp} = min\,\{C^{exp}, q_0^{art} \times \left(1 - \frac{P_1}{100}\right) + q_0^{exp}\} \tag{3}$$
$$q_1^{art} = Q_{art} \times \frac{P_1}{100} \tag{4}$$
$$q_2^{exp} = q_1^{exp} \times \frac{P_2}{100} \tag{5}$$
$$q_2^{art} = min\,\{C^{art}, q_1^{exp} \times \left(1 - \frac{P_2}{100}\right) + q_1^{art}\} \tag{6}$$

where,

Q_{exp} : Observed input flow from upper end of expressway [vehs/h]
Q_{art} : Observed input flow from upper end of arterial [vehs/h]
C^{exp} : Given maximum allowable flow per unit time on expressway [vehs/h]
C^{art} : Given maximum allowable flow per unit time on arterial [vehs/h]
P_1 : Observed rate of vehicles continuously use arterial before and after on-ramp [%]
P_2 : Observed rate of vehicles continuously use expressway before and after off-ramp [%]

Under this assumption on network in **Fig.1**, bottleneck is set at lower end of each expressway and arterial to limit the number of outgoing vehicles from this network. Now, these points represent the bottleneck on normal section such as sag part or an entrance of tunnel and capacity at this point is set as C_{BN}^{exp} and C_{BN}^{art} respectively which satisfies both $C_{BN}^{exp} \leq C^{exp}$ and $C_{BN}^{art} \leq C^{art}$.

Assuming that the capacity of the rampway is infinity, two cases to consider exist which excess the capacity of bottleneck: 1) at merging section and 2) at the bottleneck section. Therefore, there are four bottlenecks as shown in **Fig.2**. Moreover, if the capacity of the bottlenecks, $C^{exp}, C^{art}, C_{BN}^{exp}$ and C_{BN}^{art}, is given, whether queue is generated or not for each point is able to be judged by simple calculations below:

Table.1 Status and assigned unique number (Status Number)

*Legend: ✓ for queue is generated / × for queue is not generated

Queues generated from	Status Number															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A. Off-ramp merging	×	×	×	×	×	×	×	×	✓	✓	✓	✓	✓	✓	✓	✓
B. On-ramp merging	×	×	×	×	✓	✓	✓	✓	×	×	×	×	✓	✓	✓	✓
C. Bottleneck in arterial	×	×	✓	✓	×	×	✓	✓	×	×	✓	✓	×	×	✓	✓
D. Bottleneck in expressway	×	✓	×	✓	×	✓	×	✓	×	✓	×	✓	×	✓	×	✓

*Note: Status #8, #9, #12, #13 will not appear under the condition stated in this paper.

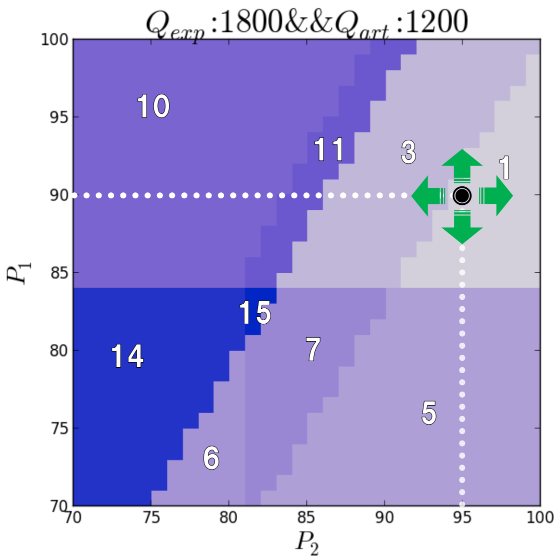

Fig.3 An example of the Status Map for (Q_{exp}, Q_{art}) = (1800, 1200) and described Status(#1) on the Map when observed pair of (P_1, P_2) = (90%, 95%)

*Note: current Status might be changed according to arrays as a result of traffic management

A. Queue from off-ramp merging is generated $if\ q_1^{exp} \times \left(1 - \frac{P_2}{100}\right) + q_1^{art} \geq C^{art}$ (7)

B. Queue from on-ramp merging is generated $if\ q_0^{art} \times \left(1 - \frac{P_1}{100}\right) + q_0^{exp} \geq C^{exp}$ (8)

C. Queue from bottleneck in arterial is generated $if\ q_2^{art} \geq C_{BN}^{art}$ (9)

D. Queue from bottleneck in expressway is generated $if\ q_2^{exp} \geq C_{BN}^{exp}$ (10)

Now, for each bottlenecks, state is divided only into two ways: queue appeared or not. Thus, in a whole network, 16 (2^4) queuing patterns may appear. Therefore, call these calculated queuing patterns as "Status" and assign unique number (#0 through #15) shown in **Table.1** for each Status. Of course, every set of $(P_1, P_2, Q_{exp}, Q_{art})$ have only one Status, respectively. However, under these conditions, due to the conservation law shown in **Eq(1)-(6)**, Status #8, #9, #12, #13 will not appear and actually only 12 queuing patterns occur.

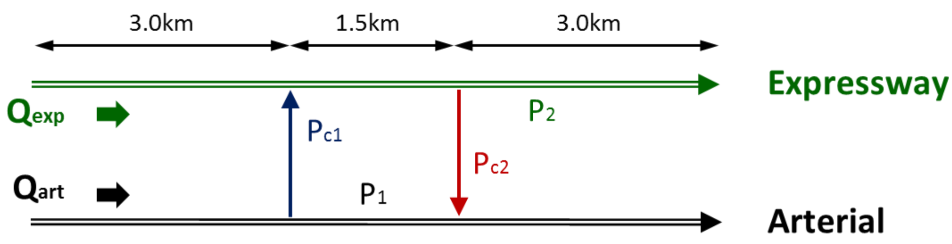

Fig.4 Detailed test sight

2.3 Drawing method of Status Map

To observe the difference of Status when P_1 and P_2 is variable (Q_{exp}, Q_{art} is fixed), color plot for $P_1 - P_2$ coordinated axes can be drawn. This map represents the Status for each (P_1, P_2) and is named as Status Map. An example of Status Map shown in **Fig.3** describes the distribution of each Status. In this paper, Status Map is described for discrete value of P_1 and P_2 from 70% to 100% by 1%.

Status map is just the way to visualize the distribution of each Status and Status Map itself has no significant sense for users of the expressway. However, as is mentioned later, this map is essential from the viewpoint of expressway control authority when applied for traffic control strategy. Moreover, current Status for observed turning percentage (P_1, P_2) can be acquired immediately on this map: *e.g.* resulted Status for the set of observed percentage (90%, 95%) is plotted as in **Fig.3** and current Status as #1 is acquired at once. If (P_1, P_2) can be controlled in some way, nexus of some management can be described as arrays in **Fig.3**.

2.4 How Status Map will be used

As is discussed above, calculation to acquire Status Map is a kind of static analysis because, as in **Eq(1)-(10)**, given parameter is constant through single set of calculations. However, obviously, some interactions affect the generation of the queue...capacity of the bottleneck is not constant even for the same section and traffic flow rate changes time to time.

Even though it is true, if the positive relationship between this static Status Map and the amount of delay deduced by dynamic analysis exists, traffic control at time t using Status Map may works to minimize the increment of congestion from time t to time $t+\tau$ under the situation that traffic control is conducted in every time interval τ. In other words, to develop a future traffic control method based on Status Map, knowledge on the traffic situation at time $t+\tau$ as the result of the control at time t should be required.

3. VALIDATION

In this chapter, we analyze the effectiveness of the Status Map to express queuing pattern, comparing the Status Map with the amount of congestion calculated by a macro simulation model. As is mentioned before, this validation step aims to quantify the congestion on this network for each turning percentage (P_1, P_2) with dynamic simulation and, then, compare with static analysis by overlapping the result on the same field to acquire knowledge on the relationship.

Table.2 Given parameters of the experiment (equal for each scenario)

	Free Flow Speed [km/h]	Maximum Flow C_{exp}, C_{art} [vehs/h]	Time Instant [s]	Jam Density [vehs/km]	Wave Speed Ratio
Expressway	90	2000	20	150	0.2
Arterial	54	1350			

Table.3 Given parameters of the experiment (different for each scenario)

Scenario No.	Q_{exp}, C_{BN}^{exp} [vehs/h]	Q_{art}, C_{BN}^{art} [vehs/h]	γ_c	* C'^{exp}_{BN} [vehs/h]
a - 1	1800	1200	1.0	1800
a - 2	1800	1200	0.3	675
b - 1	1750	1000	1.0	1750
b - 2	1750	1000	0.3	675

*Note: C'^{exp}_{BN} denotes the diminished capacity under incidental condition.

If this Status Map as a result of static analysis relates to travel time of the vehicles in some way, in other words, if they have different (steepest) descent direction of travel time per each numbered district (#0 through #15), static Status Map is still useful method to diminish travel time of the traffic by controlling (P_1, P_2) based on the Status Map drawn according to observed (Q_{exp}, Q_{art}).

3.1 Validation method

In order to analyze the effectiveness of Status Map, the result of travel time analyzed with the Cell Transmission Model (CTM) based macro simulator proposed in Daganzo (1994) and Daganzo (1995) will be introduced. On this CTM based simulator, the movement of the vehicles forward is reproduced by the transference of the vehicles to the next cell. The reason for employing this simulator is that nature of queuing in the dynamic traffic flow is correctly represented though this simulator requires less parameter.

To evaluate the amount of congestion on the network, total delay time is frequently used as a criterion. However, this is generally calculated as the difference between total travel time and free flow travel time for the whole replication period, therefore, this criterion has a significant problem: total delay time never shows what is really happening on this network just at time *t*. To solve this problem, We introduce an criterion Instantaneous Congestion Ratio (ICR(t)), this ratio aims to evaluate the congestion on this network only by using the output data just at time *t*. In this comparison, to evaluate the amount of delay immediately after five minutes spent, ICR(t=5[min]) is selected as the scale of evaluation.

$$ICR(t) = \frac{\sum_{i \in cells} n_i(t) - \sum_{i \in cells} y_i(t)}{\sum_{i \in cells} y_i(t)} \times 100\ [\%] \qquad (11)$$

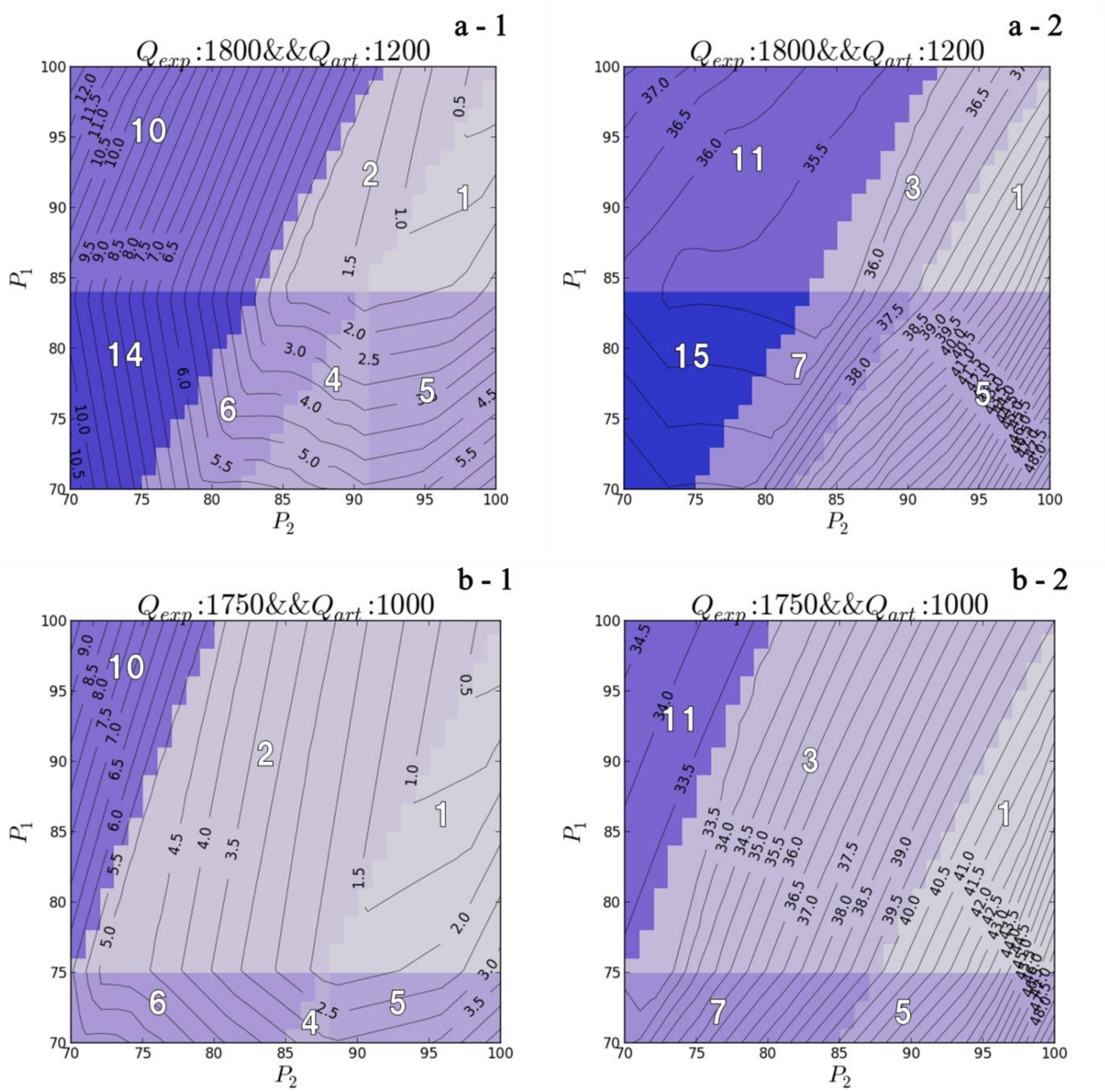

Fig.5 Result as an integrated map for different parameter

where,

$n_i(t)$: Number of vehicles inside cell *i* at time step *t*

$y_i(t)$: Number of vehicles moved from cell *i* to cell *i+1* at time step *t*

3.2 Test Scenario

Analysis is conducted on the test road section shown in **Fig.4** which basically follows **Fig.1** and other given parameters required for CTM based simulation are also shown in **Table.2**. Under these conditions, start the analysis with assumption that no queues exist on the network at the beginning of analysis. Traffic flow on both expressway and arterial is critical flow in ordinary situation (i.e. without incident).

Table.3 describes scenarios conducted in this study. The flow and bottleneck capacity under the scenario a is larger than scenario b, therefore, in scenario a, queues from merging occurs more frequently. The bottleneck capacity under Scenario 2 is smaller than scenario 1. This scenario 2 represents incident situation. The parameter γ_c denotes the ratio of bottleneck capacity compared to the ordinary condition.

3.3 Validation result

In order to clarify the relationship between Status Map and congestion state, the Status Map is overlaid with the ICR calculated by CTM. Color plot behind represents Status, as a result of static analysis and contour map represents ICR [%] as the result of CTM based simulator. This comparison aims to test whether each Status originally have same tendency inside itself or not and to determine whether good Status or poor Status in terms of delay exists or not.

Results as the integrated map are shown in **Fig.5**. In general, contours tend to bend almost according to the edge of Status, which makes descending direction of ICR contour variable for each Status and, thanks to this bending on the edge of each Status, descending direction in some Status is different from another Status, but quite the same inside each Status. Thus, queuing pattern definitely shows the tendency of the amount of congestion.

When comparing the different scenarios in terms of input flow, such as **Fig.5a-1** and **5b-1** or **Fig.5a-2** and **5b-2**, shape of ICR contour have similar tendency not with the set of (P_1, P_2) but with the Status distribution. This result implies the hypothesis that queuing pattern have significant influence on the amount of congestion as mentioned in **Section.2**. This tendency is also observed when comparing in terms of diminished capacity under incidental condition, such as **Fig.5a-1, 5b-1** and **Fig.5a-2, 5b-2**, and this result indicates that concept of Status Map might also be applicable under the incidental condition.

However, the place bending occurs in **Fig.5** doesn't totally agrees with the border between Status #2 and #10, #6 and #14 and #7 and #15. Result of time-to-time examination on CTM based macro simulator shows that this difference is caused by the ill-definition of initial condition when fulfilling the network before analysis. For example, in **Fig.5a-1**, status number for (P_1, P_2) = (75%, 80%) is #6 on Status Map. However, (P_1, P_2) = (75%, 80%) is located in the left bound of bending and, result of time-to-time examination shows that, at (P_1, P_2) = (75%, 80%), small queue generated from off-ramp merging exists and actual Status is #14, different from what acquired from Status Map. That means this mistake is caused not by the error of Status Map itself but by the setting of test environment.

From the different perspective, these results in **Fig.5** indicate that delay grows slowly when vehicles are allocated to load nearly equal on both bottlenecks, such as Status #3, #4 and #7, and, conversely, delay grows too fast when Status is #10 and #14. This is, of course, the nature of traffic control and, as in mentioned in **Section.1**, this is why information provision is recently conducted. That means, so-called "good Status" exists when vehicles are allocated nearly equal on both bottlenecks. However, when control is implemented under this scheme, in reality, arterial might be strongly disturbed by control. This problem is without the reach of this research, but this result implies that control toward the good Status might strongly disturb the situation on arterials.

However, Status Map can't take stretching of the queue into consideration because, as in **Section.2**, this method just focuses on the queuing pattern, not the length. Thus, when this method is applied for the situation queue stretches beyond intersection or another bottleneck, huge error might occur and control wouldn't work. This is the limitation of previous Status Map and this problem should be resolved to apply for the real traffic network.

4. CONCLUSION

In this study, Status Map which presents static queuing pattern was developed. It represents the places of the head of the queues under the certain given demand. The Status Map was illustrated by comparing the bottleneck capacity and the traffic flow. Validation result with CTM based simulator showed that the static queuing pattern in the Status Map represented the amount of delay.

The Status Map illustrated the queuing patterns during the incidental traffic congestion. Another aspect of this study reveals that the generation of queues on arterial under the controlled situation can be evaluated and, in some cases, traffic control based on this Status Map might disturb the traffic flow on arterial. This problem itself is without the reach of this study, but this is still useful if condition on arterial can be evaluated.

On the other hand, there are some remained problems on the Status Map. When it is applied as the real control method, the Status Map may not always present the amount of congestion. For example, when queue stretches beyond the intersection or another bottleneck, traffic flow for each subsection can’t be calculated from **Eq(1)-(6)** in **Section.2** and difference between actual generation of queue and estimated generation of queue calculated on Status Map certainly exists. As mentioned earlier, descending direction of ICR is totally different between each Status, therefore, wrong estimation of the current Status may lead the current Status in bad way.

As the future works, traffic control methodology with the Status Map will be developed. To control traffic with the information provision, consideration on the method to promote or restrain outgoing vehicles from off-ramp is required. In addition to this, this method should be expanded spatially for various networks. As is known, total optimization is not equal to the summary of sub-optimization. This paper describes the result for a smallest unit under both upper and lower traffic flow is neglected. That means, it is crucial to expand specially and show the efficiency whether this method is enough for practical use in an empirical way.

REFERENCES

Bogenberger, K., May, A. D. (1999) Advanced Coordinated Traffic Responsive Ramp Metering Strategies, California PATH Working Paper UCB-ITS-PWP-99-19

Sasaki, T., Myojin, S. (1968) Ramp Metering Method for Urban Expressway Network, Transportation Engineering, Vol.3, No.3, pp.8-16 (written in Japanese)

Papageorgiou, M., Hadj-Salem, H., Blosseville, J. M. (1991) ALINEA: A Local Feedback Control Law for On-Ramp Metering, Transportation Research Record Vol.1320, pp.58-64

Papageorgiou, M., Hadj-Salem, H., Middelham, F. (1997) ALINEA Local Ramp Metering: Summary of Field Results, Transportation Research Record Vol.1603, pp.90-98

Yoshii, T., Shiomi, Y., Son, X., Kitamura, R. (2008) Development of a ramp metering method to improve an area network flow performance using macroscopic fundamental diagram, Proceedings of Infrastructure Planning (CD-ROM), JSCE, Vol.37, No.101 (written in Japanese)

Nikolas, G., Daganzo, C. F. (2007) Macroscopic Modeling of Traffic in Cities, 86th Annual Meeting of the Transportation Research Board, Washington D.C.

Arnott, R., de Palma, A., Lindsey, R. (1991) Does Providing Information to Drivers Reduce Traffic Congestion?, Transportation Research Part A, Vol.25A, No.5, pp.309-318

Oguchi, T., Satoh, T., Shikata, S. (2005) The Providing Effect of Traffic Information on Alternative Route Choice Behavior in Congested Traffic Condition, Infrastructure Planning Review, JSCE, Vol.22, No.4, 799-804 (written in Japanese)

Daganzo, C. F. (1994) The Cell Transmission Model: A Dynamic Representation of Highway Traffic Consistent with the Hydrodynamic Theory, Transportation Research Part B, Vol.28B, No.4, pp.269-287

Daganzo, C. F. (1995) The Cell Transmission Model: Network Traffic, Transportation Research Part B, Vol.29B, No.2, pp.79-93