EVALUATION OF AN AREA METERING CONTROL METHOD USING THE MACROSCOPIC FUNDAMENTAL DIAGRAM

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ABSTRACT

This Paper proposed an effective area metering control method applied for urban expressway road networks. The control is carried out using the relationship between aggregated traffic flow and aggregated traffic density at a designated road network area, which is one of the Macroscopic Fundamental Diagram (”MFD”, thereafter). It is expected that the concept of MFD is introduced to traffic control measures in oversaturated urban road networks. We established an area metering control method based on the MFD concept and verified the effect of the method by applying it to Hanshin Expressway road network using a dynamic traffic simulation. As a result, it was shown that the area metering control method can successfully keep the area traffic density at a moderate level and can achieve high flow in the area. Also, it is shown that the method has high potential to reduce the total travel time.

Keywords: control, applications, metering, macroscopic, urban freeway, oversaturated network

INTRODUCTION

As for the actual traffic controls to mitigate the traffic congestion in an oversaturated road network area, there are several examples in some cities. For example, in Osaka metropolitan area, Hanshin Expressway (1979) has been carrying out a ramp metering control since 1980 for the purpose of mitigating the traffic congestion. A ramp metering control has been carried out for inbound traffic when the flow on the CBD road network is expected to decreased due to overloaded traffic. Ernst, Deputy Director of Zurich Transport Authority Zurich, (2000) reported that they introduced a new traffic light operating system, in which the flow towards an overloaded area is restricted while the flow towards an underutilized area should be promoted. The system tried to prevent overcrowding state of the road network by continuous counting of traffic area and metering of access to maintain the mobility of cars at a stabilised level. He said, "Every housewife knows that a washing machine must not be completely filled if a good result is to be achieved. The same applies to the urban road network." Both of the control measure must work well to avoid the malfunction of those road networks. They don't present, however, the detail of the control algorithm with a clear strategy supported by academic theory.

Sasaki et al. (1968) proposed a ramp metering strategy, in which the cars coming onto the expressway at each entrance ramp are limited to avoid congestion on the whole network. The system calculates the maximum allowable inflows by solving a linear programming problem once in every five minutes using the data from detectors installed on the expressway and at all ramps. This strategy has been tried to apply actual traffic control because it seems to be reasonable and effective. However, it has not been introduced to the actual system yet due to its drawbacks. The first, its framework is static. In order to alleviate this problem, Sasaki et al. (1987) proposed to adopt fuzzy rules to the control system so as to make the system be robust for uncertainties. The second, its performance is heavily dependent on the accuracy of estimated OD volumes.

Daganzo (2007) established the idea of monitoring and controlling aggregate vehicular accumulations at the neighbourhood-level to improve city mobility by avoiding the gridlock state. He proposed a macroscopic relationship between total outflow from the system and aggregate accumulation. Geroliminis and Daganzo (2007) proposed an observation-based model for oversaturated urban road networks based on the macroscopic control strategies. The effect of the proposed model was tested by applying it to San Francisco network using a simulation. Then, it was shown that the total outflow of the system increased by 34% by carrying out a control method. The study in this paper is done with reference to this concept.

This paper proposed an effective ramp metering control for an oversaturated urban expressway network. It is based on the MFD concept and is carried out on a designated network area. Then, the area metering control algorithm is verified by empirical analysis using a traffic simulation.

MACROSCOPIC FUNDAMENTAL DIAGRAM

This paper defines a fundamental diagram on a designated road network consisting of many links. Two variables are introduced, aggregated traffic flow ("ATF", thereafter) and aggregated traffic density ("ATD", thereafter). The former indicates vehicle miles per unit time on the whole designated area, and the latter indicates the number of vehicles on the area. These are calculated as equation (1) and (2).

$$Q = \sum_{i \in L} (q_i \times d_i) \tag{1}$$

$$K = \sum_{i \in L} (k_i \times d_i) \tag{2}$$

where,

Q : aggregated traffic flow [vehs・km/h]

q_i : traffic flow on link i [vehs/h]

d_i : length of link i [km]

L : link set of the study road network

K : aggregated traffic density [vehs/area]

k_i : space mean density on link i [vehs/km]

The expected relationship between these two variables is described in Figure 1. The MFD of "OABC" can be recognized from the figure. It indicates the properties; the ATF (Q) is increasing in proportion to the ATD (K) when K value is rather small, on the other hand Q value is decreasing as K value increases when K value exceeds a certain amount. This decrease is considered to be caused by gridlock phenomena. In other words, once the number of vehicle on the road network has increased exceeding the certain amount, the more vehicles entering the road network cause the decline of its performance. Hence, the traffic entering the road network should be limited so as not to cause this phenomenon. Under the situation when the overflow of traffic is entering the network, the high performance must be achieved if K value is kept in the proper level shown by the shadow area in Fig.1. Based on this property, this paper proposes an area metering control method which aims at keeping the proper aggregated traffic density.

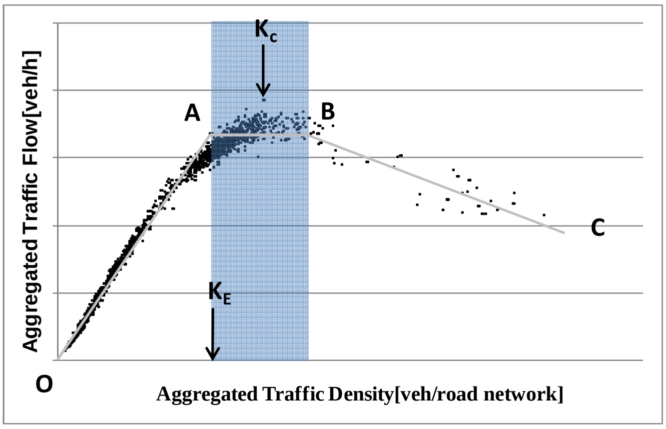

Figure 1 – Expected Macroscopic Fundamental Diagram

AREA METERING CONTROL METHOD

This chapter describes an algorithm of the area metering control method. As explained above, the algorithm aims at keeping the proper traffic density when overflow of traffic rushes into the road network area and K value is expected to exceed the certain amount.

The ATD, K, in a unit control time interval Δt is calculated by the equation (3).

$$K(t+1) = K(t) + \Delta t \cdot I(t+1) - \Delta t \cdot O(t+1) \tag{3}$$

where,

$K(t)$: aggregated traffic density at the end of time interval t [vehs/network area]

$I(t)$: the average vehicle inflow rate entering into the network during the time interval t [vehs/h]

$O(t)$: the average vehicle outflow rate exiting from the network during the time interval t [vehs/h]

The inflow rate at the next time interval, $I(t+1)$, can be controlled within the demand by carrying out some metering method. However, it is impossible to keep the ATD a stable value. Because it is impossible to predict the exact outflow rate $O(t+1)$ in advance. Hence, observable value of $O(t)$ instead of $O(t+1)$ is used to calculate the controlled inflow volume of the next time interval. At the all controlled entrances, this volume should be set less than the inflow demand including the vehicles at the spot queue. If it is set at the higher value than the inflow demand, the actual inflow cannot keep the controlled inflow rate.

After the target value, Kc, is given by analysing MFD using the observation data, the controlled inflow rate, $R(t+1)$, is calculated by solving the equation,

$$K_C = K(t) + \Delta t \cdot R(t+1) - \Delta t \cdot O(t) \tag{4}$$

Although this method might not keep the ATD at K_C, the high level of flow can be achieved if the proper density has a margin as shown in Fig.1. K_C is one of the most important parameter and should be determined by the observation data.

The control strategy when it starts and whether it proceeds to carry out or not, are also essential factors. As for the decision to start, the K_C value can be effectively used as a boundary index. In the proposed algorithm, the control starts when the aggregated traffic density exceeds the K_C value. On the other hand, K_C value is not proper index for the decision to terminate it. If both of the decisions are made by using the same value, there would cause too many times of switching. Therefore, the value, K_E, should be set lower than the K_C with some margin on condition that it is held the proper level shown by the shadow area in Figure 1. The lowest value in the proper level is selected as K_E value in the proposed algorithm.

The proposed control algorithm is as follows.

[Step 0]
Setting the parameters, K_C , K_E and Δt.
[Step 1]
The control time interval $t = t + 1$.

[Step 2]
Calculating the ATD, K, by the observed traffic counts.
If $K > K_C$, go to step 5.
[Step 3]
If the control is off at the previous time interval, no control is carried out in the time interval, and go to step 1.
[Step 4]
If $K < K_E$, no control is carried out in the time interval, and go to step 1.
[Step 5]
Choosing the controlled links at which the inflow traffics are limited.
[Step 6]
Setting the control inflow traffic rate at the links determined in step 5.
[Step 7]
Carrying out the control during the time interval, and go to step 1.

EMPIRICAL ANALYSIS

In this chapter, the effectiveness of the proposed control method is verified by carrying out an empirical analysis using dynamic traffic simulation, SOUND, established by Yoshii et al.(1995)

Study Network

The study network area is shown as Figure 2. It represents a part of Hanshin expressway road network that is one of the oversaturated urban expressway networks in Japan. The network area is formed from a loop, which is composed of 8.2 km length of multi lane expressway and on which one way traffic control is applied. 13 inflow links and 13 outflow links are connected with the loop.

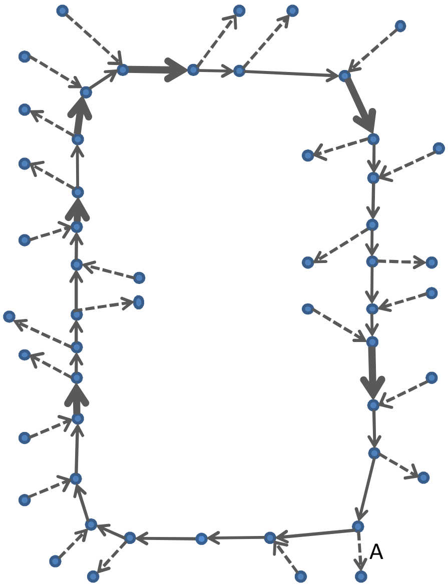

Figure 2 – Study Network

OD Demand

13 Origin×13 Destination of hourly OD demands are given to every one hour time interval, which are calculated by equation(5) based on the survey results by Hanshin Expressway public corporation(1994).

$$T_{ij}(t) = T_{ij}^{24} \times h(t) \tag{5}$$

where,
$T_{ij}(t)$: hourly OD traffic from i to j at time interval t [vehs/h]
T_{ij}^{24} : daily OD traffic from i to j given by the survey results [vehs/day]
$h(t)$: the ratio of hourly traffic to daily traffic entering whole Hanshin Expressway network at time interval t.

Simulation Parameters

SOUND, the dynamic traffic simulation is one of the meso-scopic model, which requires the capacities of each link as input. Then, using the capacity value, the fundamental diagram is formed as Figure 3. Slopes of the lines in free flow state and in congested flow state are set 60[km/h] and -20[km/h] respectively. The scanning time interval is set as 1 second. The vehicles on the network move at each time interval so as to keep the relationship between spacing and velocity. The former one is calculated by taking reciprocal of density and the latter one is calculated by dividing the flow by the density. The capacity is only the parameter of the diagram, and it was given by multiplying the number of lanes by the constant value, 1,800[vehs/h], except the 6 of bottleneck links shown in bold lines in Figure 2. The capacities of these 6 links are calculated based on the observed counts by detectors in accordance with the process below. The data composes of 5min. traffic volumes, occupancy and averaged velocity observed from Jun. 4(Mon.) to Jun. 8(Thu.) in 2007.

1. Extracting the time intervals when the averaged velocities at all of the links on the loop are higher than 50[km/h].

2. At each links, 5 percentile value of the averaged velocity is used as the boundary between free flow state and congestion state.

3. At each links, extracting the time intervals among ones determined in the process 1, which satisfies the condition that the state of the next link is free flow and the state of it is congested flow.

4. At each links, taking an average among the traffic volumes in the time intervals determined in the process 3 above. This value is fixed as the capacity.

Figure 4 shows an example of this method. The density is evaluated by assuming average vehicle length. The slope of the line indicates the boundary value in the process 2, and the cross marks indicate the data extracted in the process 4.

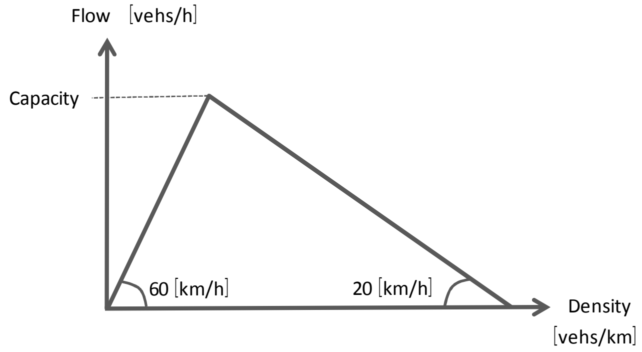

Figure 3 – Fundamental Diagram

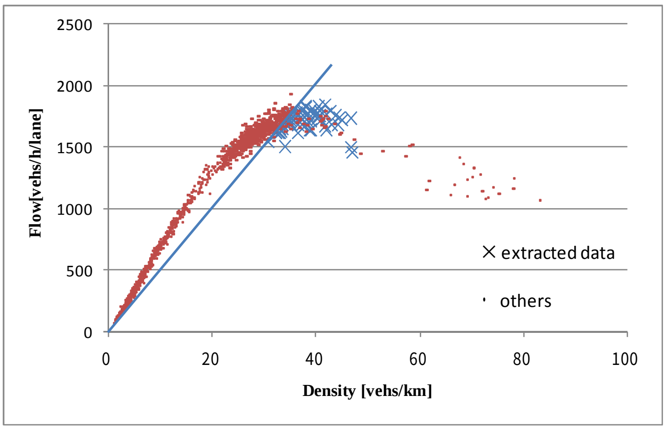

Figure 4 – Example of the Observation Data

Macroscopic Fundamental Diagram

In this study, OD traffic generating from 3 a.m. to 10 a.m. are loaded to the study network by using SOUND. The simulation is terminated when every vehicle have completed their trips.

Scatter plots in Figure 5 describes the relationship between ATF (Q) and ATD (K). The figure shows only the trend that the ATF increases in proportion to the ATD. In this case, the ATD never exceeds the Kc value, at which the high flow can be achieved. In other words, usual traffic never cause gridlock phenomenon in the study network.

Next, in order to raise gridlock, simulation is carried out assuming the capacity reduction at a link caused by a traffic accident. The half of the original value is given to the capacity at link "A" shown in Figure 2. Figure 6 describes the results of the relationship between Q and K. The diagram in the figure indicates a Macroscopic Fundamental Diagram on which the traffic states follows if the traffic states at all links are "free" or they are "congestion". Q value and K value at the point "C" in the figure are calculated by equations (6) and (7) respectively. They are obtained by taking summation of the states at the critical point. K value at the point "J" is also calculated by equation (8), which takes summation of the vehicles existed on each link under the jam density. The figure shows that all of the points are plotted not only on the diagram OCJ but inside it, because the state must appear that some links are "free" states and the other links are "congestion" states. The figure indicates that approximately 700 to 1,000 of K can achieve high Q value, and higher K value causes the reduction of it.

$$x_C = \sum_{i \in R} (k_i^c \times d_i) \tag{6}$$

$$y_C = \sum_{i \in R} (q_i^c \times d_i) \tag{7}$$

$$x_J = \sum_{i \in R} (k_i^{jam} \times d_i) \tag{8}$$

where,

x_I : the aggregated traffic density at point I [vehs/area]
y_I : the aggregated traffic volume at point I [vehs km/h]
k_i^c : critical density of link i [vehs/km]
k_i^{jam} : jam density of link i [vehs/km]
q_i^c : capacity of link i [vehs km/h]
d_i : distance of link i [km]
R : link set located in the designated area

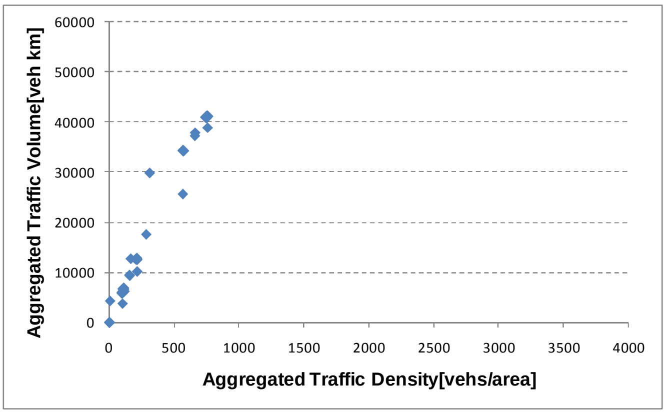

Figure 5 – Aggregated Q-K Relationship in Usual Case

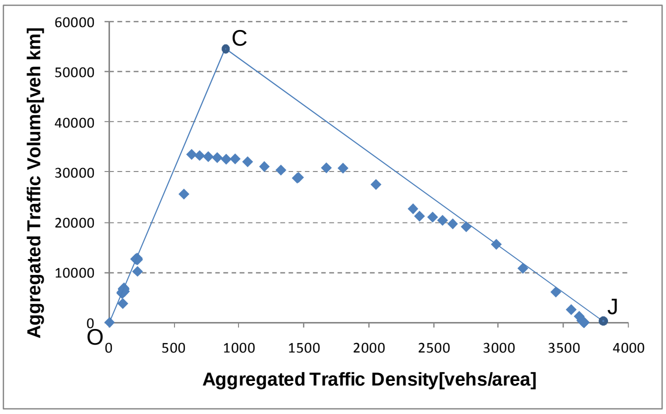

Figure 6 – Aggregated Q-K Relationship in Accident Case

Area Metering Control Algorithm

The traffic metering control is carried out basically according to the algorithm described before. The parameters are set as follows;

K_C = 914[vehs/area],
K_E = 700[vehs/area],
Δt = 5[min.].

K_C value is the K value at point "C" calculated by equation (6), and K_E value is the minimum K value which can achieve high Q value shown in Figure 6.

When the control is carried out, the controlled links at which the inflow traffics are limited are determined in the step.5. In this study, the controlled links are chosen among the links by which connect with the loop (see Figure 2). The decision is done by checking the traffic state of the next downstream link at the previous time interval. Only the links whose downstream link is "congestion" state are chosen as one of the controlled link. The allowed inflow traffic rates at the links are determined by equation (9). The each allowed inflow rate is calculated by multiplying the actual inflow rate at the last time interval by the same ratio.

$$N_l(t) = q_l(t-1) \times r(t) \tag{9}$$

$$r(t) = \left[1 + \frac{\sum_{i \in B} q_i(t-1) \cdot \Delta t - \{K(t-1) - K_C\} - \sum_{i \in A} q_i(t-1) \cdot \Delta t}{\sum_{i \in C} q_i(t-1) \cdot \Delta t} \right] \tag{10}$$

where,

$N_i(t)$: controlled traffic flow rate at link i in time interval t [vehs/h]
$q_i(t)$: average traffic flow rate at link i in time interval t [vehs/h]
$K(t)$: aggregated traffic density at the end of time interval t [vehs/area]
$r(t)$: multiplier at time interval t
A: inflow link set toward the loop
B: outflow link set from the loop
C: controlled link set which flow rate is limited in the next time interval

Evaluation Results

As explained above, usual traffic never cause gridlock phenomenon in the study network. The evaluation is done on the assumption that a capacity reduction is appeared due to accident. In the scenario, the half of the original value is given to the capacity at the link A during one hour, from 8 a.m. to 9 a.m. The value is set as 1,800[vehs/h] instead of the original value of 3,600[vehs/h]. In total, 70,707[vehs] are generated in the simulation time.

Table 1 compares the total travel times in both cases, with/without the area metering control. It shows that the total travel time and the total delay are definitely reduced by carrying out the area metering control. Note that, the travel time includes "waiting time at the inflow links". In other words, by carrying out the area metering control, smoother traffic can be achieved not only in the loop but in the whole study network. Figure 7 shows the aggregated Q-K relationship in both cases, with/without control. You can find the results that higher flow was achieved by controlling the traffic density. Figure 8 shows the transition of the ATD from 7 to 10 a.m. It indicates that the K value kept increasing in case without control after the capacity reduction. On the other hand in case with control, inflow rate was controlled from 8:15 to 10:05. The K value took the value around K_C, although it was not kept the exact value. As a result, in case without control ATF had been reduced, while by carrying out the control, ATF was recovered to higher value as shown in Figure 9.

Table 1 – Total travel time

	without control	with control
Total travel time [veh*hour]	32053	21069
Total delay [veh*hour]	28386	17402

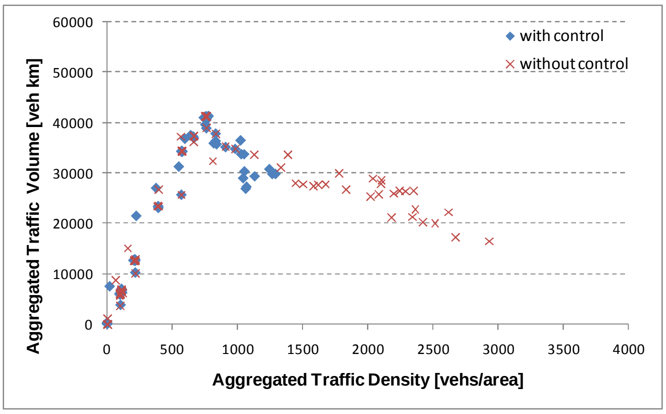

Figure 7 – Aggregated Q-K Relationship in Usual Case

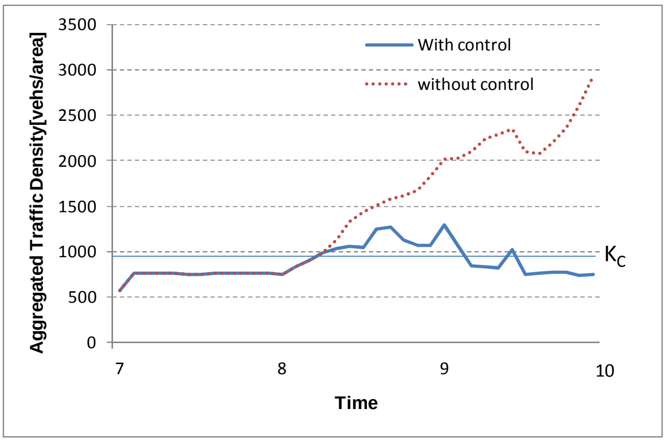

Figure 8 – Aggregated Traffic Density

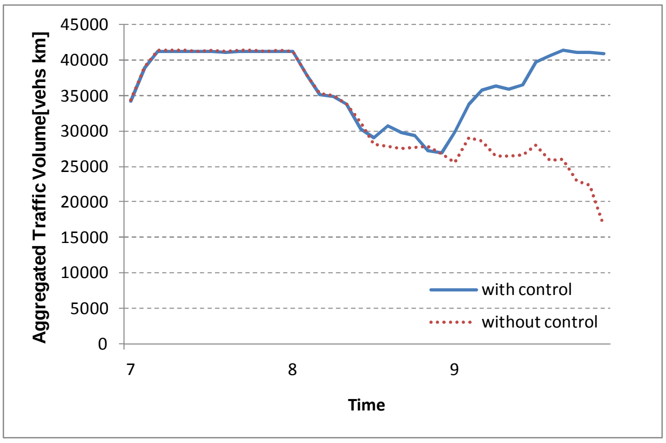

Figure 9 – Aggregated Traffic Volume

Finally, the profit of each vehicle is examined by comparing both travel times between the cases with/without control. Figure 10 describes the averaged travel time of vehicles with the same OD departing from their origin between 8 to 9 a.m. There are several OD pairs whose travel time is extremely large, because the vehicles could not enter the loop due to heavy congestion and they have to queue at the origin node in this simulation. These OD traffics sustaining a large delay can receive the great benefit in their travel time by carrying out the control. On the other hand, for the vehicles whose travel time is not so large, some OD traffics get more delay by carrying out the control. In conclusion, it is confirmed that the area metering control can mitigate traffic congestion, which is evaluated by the total travel time. Note that, it should be cared that some of OD traffic may have disadvantages.

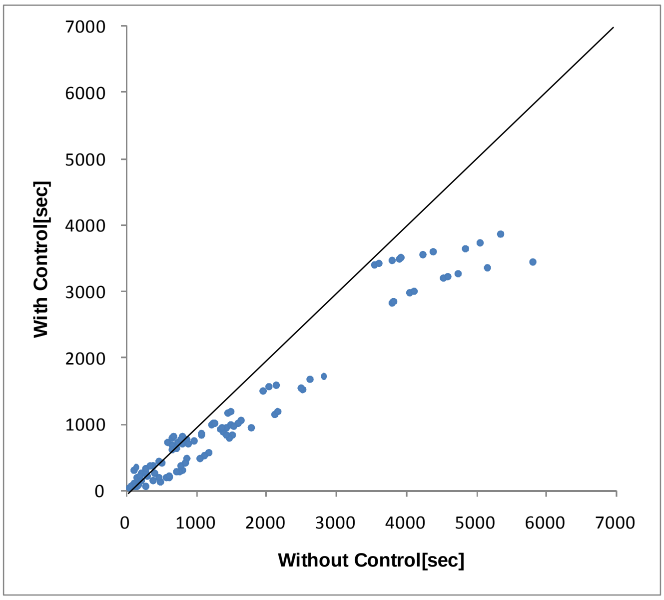

Figure 10 – Averaged Travel Time of each OD Pairs

CONCLUSIONS

In this study, an effective area metering control method is proposed, and it is verified by applying it to the Hanshin Expressway network using simulation. It is carried out so as to keep the aggregated traffic density at the proper level in which higher flow can be achieved.

As a result of the verification, it was shown that carrying out the proposed control method can improve the network performance and mitigate the traffic congestion. Still there have been many other rooms to be cleared. The first, a sufficient condition should be cleared in order to use the control effectively, that would be provided by the traffic states at the whole network. The second, analyses including surface streets, and ones of the effects on the surrounding area should be done. The third, the way how to make it fit for practical use should be considered.

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