ADAPTIVE TRAFFIC SIGNAL CONTROL USING REAL-TIME DELAY MEASUREMENT
- Consideration of Stochastic Delay -

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ABSTRACT

This research developed an adaptive traffic signal control system named as CARREN (Control Algorithm Retuning paRameters with self performance EvaluatioN) that generates signal parameters automatically to reduce network delay which is directly measured by ITS technologies. In the latest improvement of this system, stochastic demand fluctuation is considered for delay evaluation and it made the algorithm possible to work more reliably in nearly saturated condition. CARREN has been tested by simulation and field experiment. Results of both experiment show that the system reduced delay compared with the conventional selection control.

INTRODUCTION

Traffic congestion in urban area is still an important issue to be solved. One of the reasons of congestion in urban area is imperfect operation of traffic signal control. Conventional traffic signal control used in Japan, called as Program Selection Control, selects optimal signal parameters from pre-determined sets to adapt the current traffic conditions. This control has some problems. First, since the number of pre-determined sets of signal parameters is limited, the system can adapt to limited conditions. That means it can not achieve good performance in unusual condition or after change of traffic condition in the long run. Moreover, design of signal parameter sets based on degree of saturation does not guarantee minimization of congestion cost (= delay). Though adaptive controls, such as SCOOT, SCATS, MODERATO, and so on, are developed and implemented practically, it does not directly evaluate the delay itself, either.

The algorithm proposed in this study can solve these problems. This algorithm (named as CARREN) updates the signal parameters in every cycle based on delay evaluation. Delays of individual vehicles are directly measured by recently developed sensors though it is estimated in existing control. Most of the other required data such as free flow travel time or saturation flow rate can also be obtained from sensors. This means CARREN works well without periodic calibration and even in unusual condition.

In the previous study[(1)], CARREN could only evaluate deterministic delay with the assumption that measured arrival and departure patterns were the same as in the next cycle. Actually, these patterns may fluctuate cycle by cycle. In this study, this stochastic fluctuation of traffic pattern is considered to evaluate delay.

The structure of this paper is as follows: Section 2 shows the overview of CARREN. Section 3 explains how CARREN evaluates delay especially in the case of stochastic delay in relation to signal parameters. Results of simulation and field experiment are shown as in Section 4. The final section contains conclusions.

STRUCTURE OF SIGNAL CONTROL SYSTEM

The structure of CARREN is shown as in Figure 1. The required data are departure time at subjective intersections of all vehicles and travel time of sample vehicles passing through the inflow links. AVI (Automatic Vehicle Identification) sensors and ultrasonic detectors are set as in Figure 2. Since the departure time of all the vehicles is required, ultrasonic detectors are used. Travel time of each vehicle can be measured by matching the plate numbers from AVI sensors between upstream and downstream of subjective intersection.

CARREN represents current traffic conditions as cumulative flow diagrams (Figure 2). At first cumulative departure curve (at point D) is drawn as while dots by using the flow profile of ultrasonic detectors. Second, passing time at point A can be obtained as black dots. The distances between white and black dots show the travel time measured by AVI sensors. Then, by shifting these black dots as much as free flow travel time between A and D and smoothing, arrival curve can be drawn. The area surrounded by arrival and departure curve shows the delay per cycle in this subjective stream. Free flow travel time is calculated based on histogram of travel time data.

If signal parameters change, the shape of cumulative curve and delay also change. CARREN evaluates the delay when signal parameters change and searches the best combinations of parameters from neighborhood of current parameters so that the total delay of subjective network is minimized.

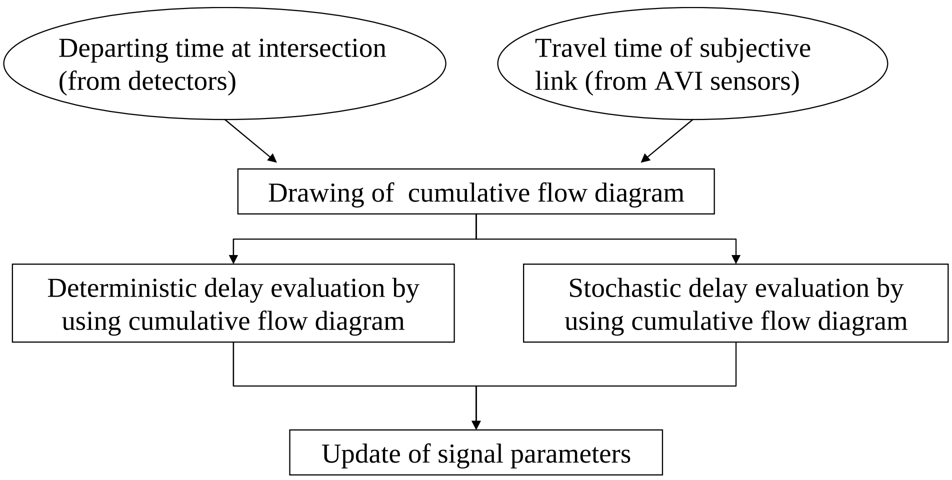


Figure 1 Structure of CARREN

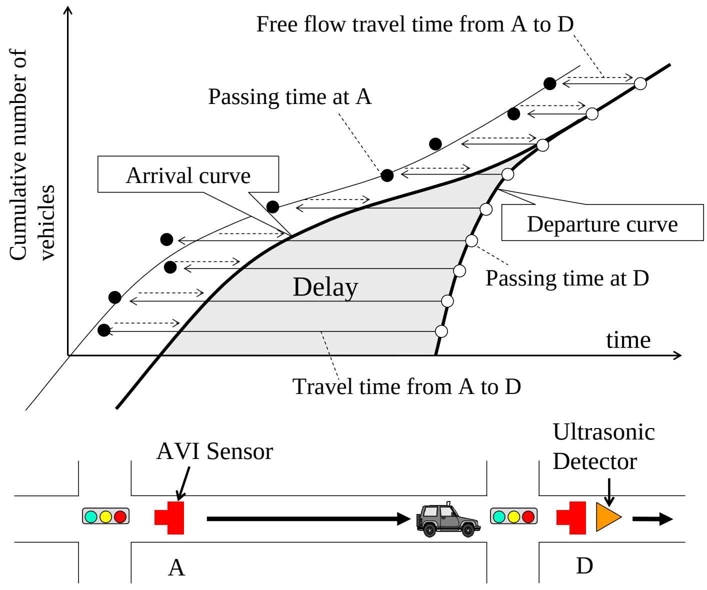


Figure 2 Cumulative Flow Diagram

DELAY EVALUATION FOR SIGNAL CONTROL

EVALUATION OF DETERMINISTIC DELAY

The delay to be evaluated can be divided into deterministic delay and stochastic delay. The deterministic delay is the delay when arrival and departure patterns are stationary. Figure 3 shows the example case that split of subjective stream is increased by Δ_G and offset and cycle time are constant. The current cumulative curve is shown as solid line. The start time of red phase becomes later by Δ_G when split is increased. Departure curve in this case will be as upper dotted line and the delay in this case can be estimated. The change of delay in case of offset and cycle time changing can be calculated in the same way. See the paper (1) for detail explanation of deterministic delay evaluation.

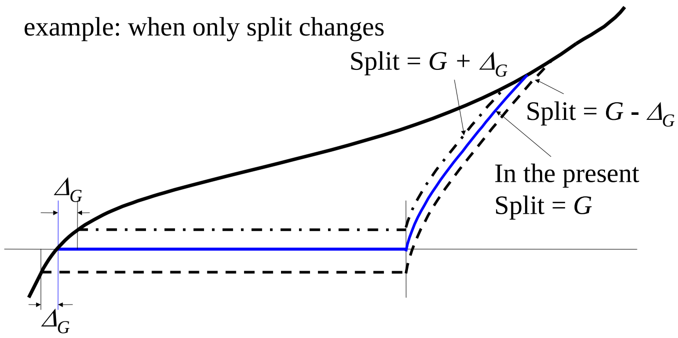


Figure 3 Change in Delay when Split changes

EVALUATION OF STOCHASTIC DELAY

In this paper, evaluation of stochastic delay is added to CARREN. We assumed the stationary demand for deterministic delay, which means the shape of the cumulative flow curve in the next cycle is the same as that of measured curve. In fact, the shape of cumulative curve is not exactly the same in every cycle, even if the expected demand rate is constant. This is because arrival and departure patterns are stochastically fluctuates cycle by cycle. The delay due to fluctuation of traffic pattern is called as stochastic delay.

If streams are in undersaturated and have sufficient splits, the stochastic delay is comparably less than deterministic delay. However, if the stream is in nearly saturated condition, the stream may sometimes overflow. Once the stream is oversaturated, some vehicles have to wait for another cycle to pass through and the delay of this stream suddenly gets large. Here let's consider the stochastic delay due to probabilistically overflow vehicles. This delay can be represented as product of expected number of overflow vehicles and cycle length. Newell(2) proposed expected delay per vehicle due to vehicles which can not pass intersection in one cycle as follows.

$$E(w_s) = \frac{IH}{2\bar{s}}\left[\frac{G}{C} - \frac{\bar{q}}{\bar{s}}\right]^{-1} \tag{1}$$

where C is cycle time, G is efficient green length and $\bar{q}$ and $\bar{s}$ are expected values of arrival rate and saturation flow rate. I can be defined as below;

$$I = \frac{(Variance\ of\ queued\ vehicles\ when\ green\ phase\ ends)}{(Expectation\ value\ of\ queued\ vehicles\ when\ green\ phase\ ends)} = \frac{Var\{qC - sG\}}{E\{qC - sG\}} \tag{2}$$

where q and s are arrival and departure rates of each cycle. H, the collection factor, is the function of I, and is between 0 and 1.

Suppose the cycle time is fixed and split of substitute stream is increased by Δ_G. The stochastic delay of 1 cycle, d_G, can be represented from (1) as following equation.

$$d_G = \frac{\partial E(w_s)}{\partial G}\Delta_G \cdot \bar{q}C = -\frac{IH\bar{q}}{2\bar{s}}\left[\frac{G}{C} - \frac{\bar{q}}{\bar{s}}\right]^{-2}\Delta_G \tag{3}$$

Change of the stochastic delay when cycle time change, d_C, is also obtained from equation (1). Equation (4) shows the change of stochastic delay when cycle time is increased by Δ_C.

$$\frac{\partial E(w_s)}{\partial C} = \frac{IH}{2sC^2}\left(G - C\frac{\partial G}{\partial C}\right)\left[\frac{G}{C} - \frac{\bar{q}}{\bar{s}}\right]^{-2} \tag{4}$$

We assume that green length of each stream change in proportion to C-L.

$$\frac{\partial G}{\partial C} = \frac{G}{C - L} \tag{5}$$

Equation (4) and (5) gives the change of stochastic delay per unit time.

$$d_C = \frac{\partial E(w_s)}{\partial C}\Delta_C \cdot \bar{q} = \frac{IH\bar{q}G}{2sC^2}\left(1 - \frac{C}{C - L}\right)\left[\frac{G}{C} - \frac{\bar{q}}{\bar{s}}\right]^{-2}\Delta_C \tag{6}$$

Evaluation of change in stochastic delay makes performance of CARREN more reliable and possible to apply not only in undersaturated but also nearly saturated conditions.

TOTAL CHANGE OF DELAY

Sum of the change of deterministic delay and stochastic delay are regarded as the total change of delay for choosing the signal parameters in the next cycle. For example in the case of deciding split, we suppose 3 cases: keeping current split, increasing by Δ_s or decreasing by Δ_s. Change of deterministic delay is estimated in each case by shifting the cumulative curve of each stream. Then, stochastic delay is calculated by Equation (3). The best case is chosen to minimize sums of the change of delay in each stream belongs to the subjective intersection. Cycle time is also chosen in the same way as split.

SIMULATION AND FIELD EXPERIMENT

STUDY AREA

The performance of the algorithm is tested both by simulation and by field experiment. For the simulation experiment, traffic simulation model AVENUE[3] is used. The study area in both tests is a part of Nagoya-Nagakute Line as shown in Figure 4.

The common settings of simulation and field experiment are as follows. 4 intersections (Intersection 2 – 5 in Figure 5) are under control of CARREN. Other "uncontrolled" intersections in Figure 5 have same cycle time as that of the 4 intersections operated by CARREN. Split and offset of "uncontrolled" intersections keep initial settings of program selection control. 27 AVI sensors and 25 ultrasonic detectors are used for the control.

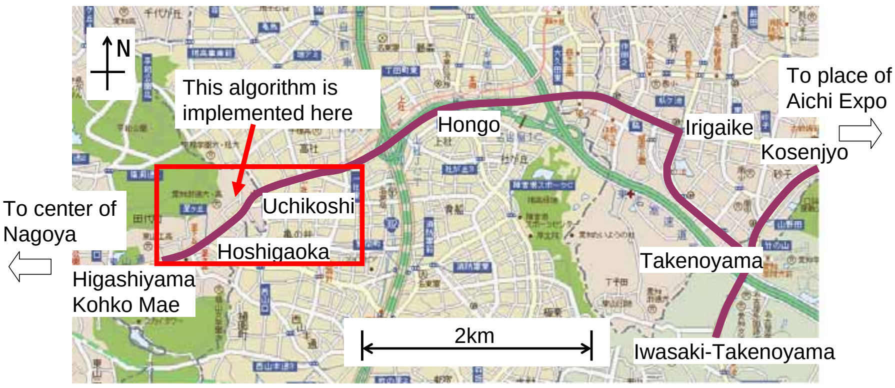


Figure 4 Study Area of Field Experiment

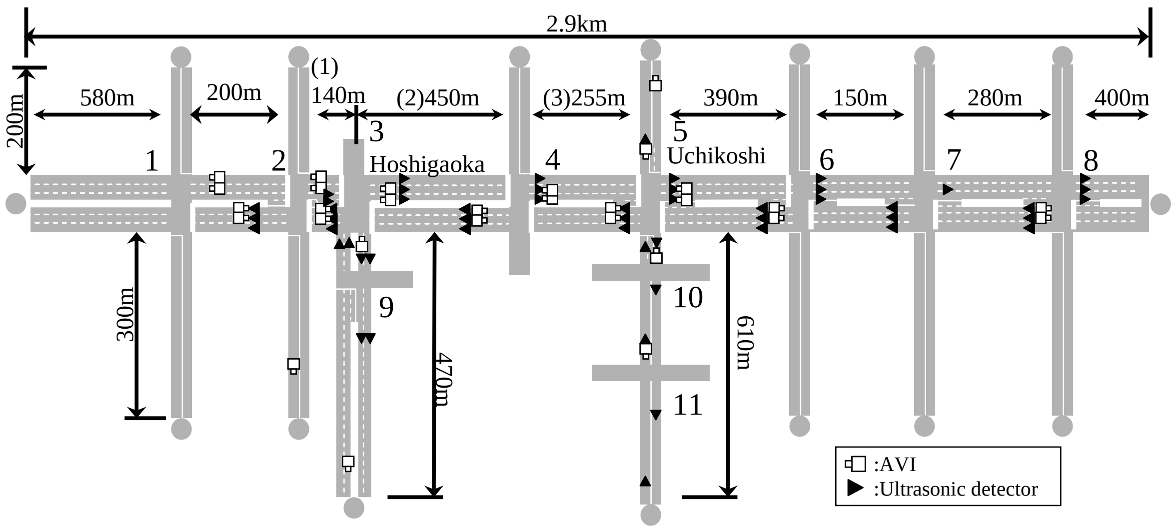


Figure 5 Study Area and Arrangement of Sensors

Simulation test has been done in the condition of morning peak (7:00-10:00). The field experiment was done during 7:00 – 16:00 from 11th to 14th of May 2004 for Program Selection Control and from 25th to 28th of May 2004 for CARREN.

RESULTS OF EXPERIMENTS

Delay in the whole network in simulation test is shown as in Figure 6. Compared to current program selection control, the total delay in the peak time and length of congestion period decreased with CARREN.

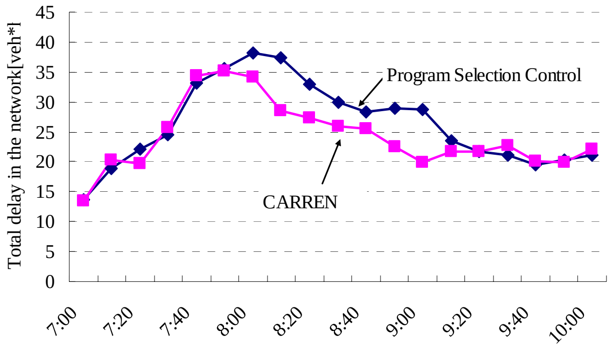


Figure 6 Total Delay in the Study Network (Simulation Test)

For the field experiment, Table 1 shows the results of average travel time measured by AVI sensors. Directions are shown in Figure 7. Because the periods of experiment are different between simulation and field test, we have to note that results of simulation and field test can not be compared directly. And although the average travel time of simulation is only in peak hours, the travel times tend to be smaller than field test. This is because simulation is ideal situation which does not have obstacles such as parking vehicles, pedestrians, inflow vehicles from roadsides, and so on.

In the simulation test, the average travel time of major road is improved but that of minor road (to north) get worse with CARREN. The reason is that CARREN gave split to major direction which has more delay, and so the travel time of minor roads increased. Total delay in this case is decreased as in Figure 6.

Table 1 Average Travel Time in the Field Test

(unit: sec)

Direction	Simulation (peak 3 hours)			Field test (one day)		
	PSC*)	CARREN	Ratio of Improvement (%)	PSC	CARREN	Ratio of Improvement (%)
To East						
E1 -> E5	179.7	163.9	8.8	157.1	125.9	19.9
E1 -> S1	99.6	96.0	3.6	96.9	97.8	-0.9
E1 -> N4	182.8	166.9	8.7	218.0	190.5	12.6
E1 -> S3	182.5	166.4	8.8	178.3	164.2	7.9
To West						
W2 -> W6	227.1	222.3	2.1	204.8	194.8	4.9
W2 -> S1	195.1	191.2	2.0	234.0	251.3	-7.4
To North						
N2 -> E5	258.6	269.6	-4.3	318.2	300.0	5.6
N2 -> W5	98.5	103.1	-4.7	100.5	89.5	11.0

*) PSC: Program Selection Control

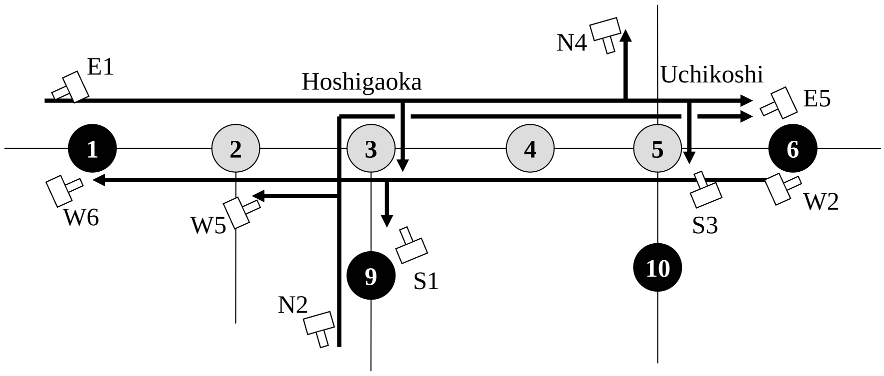
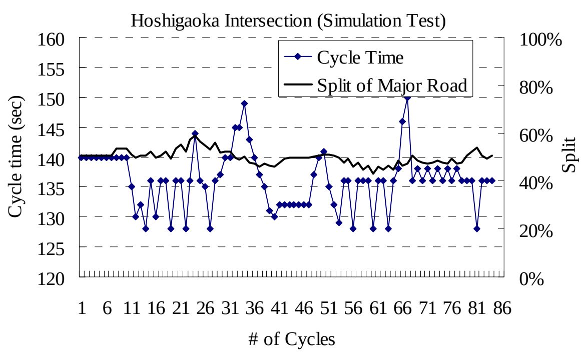


Figure 7 Arrangement of AVI Sensors for Table 1

In the field test, average travel times of most of the directions are decreased 5 – 20 % with CARREN. The reason for the increase in travel time of the route W2 -> S1 may be that sightseeing bus has stopped at Hoshigaoka intersection during the test of CARREN and it prevented the flow.

Signal parameters of Hoshigaoka intersection operated by CARREN are in Figure 8. Compared to the result in simulation test, cycle time of the field test tends to be larger than that of simulation test. That is because of the settings of free flow travel time. In the field, the shapes of cumulative flow curve are affected by inflow vehicles from small roads or from facilities at roadside. That is why larger cycle time is required in field test than in the case of simulation, where these factors are not considered.

Figure 9 represents the offset of link (1), (2) and (3) in Figure 5. Direction to east is written as positive value. The offset of link (3) in the field test oscillates because of the timing of communication between signal controller and operation center. CARREN sends new signal parameters cycle by cycle. The calculation timing is synchronized at the end of the cycle of a major intersection pre-determined by CARREN. If the cycle starting time of certain intersection is just before the starting time of base intersection, signal parameters decided at this time might not operated in the intersection. If this situation happens, offsets of these intersections may not be the expected ones and CARREN correct the offsets in the next cycle. In the link (3) of field test this situation occurs frequently. In the simulation test, this case does not occur because of calculation time and time to send signal parameters are less than the actual one.



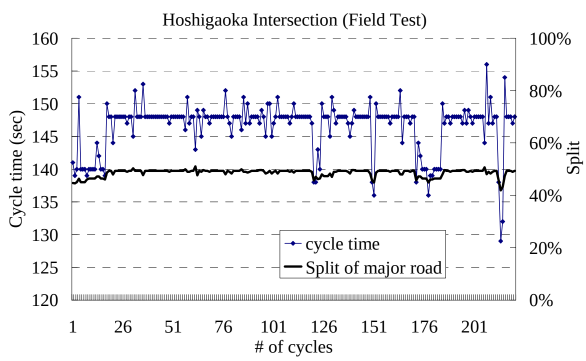


Figure 8 Cycle Time and Split of Hoshigaoka Intersection (Left Side is in Simulation Test and Right Side is in Field Test)

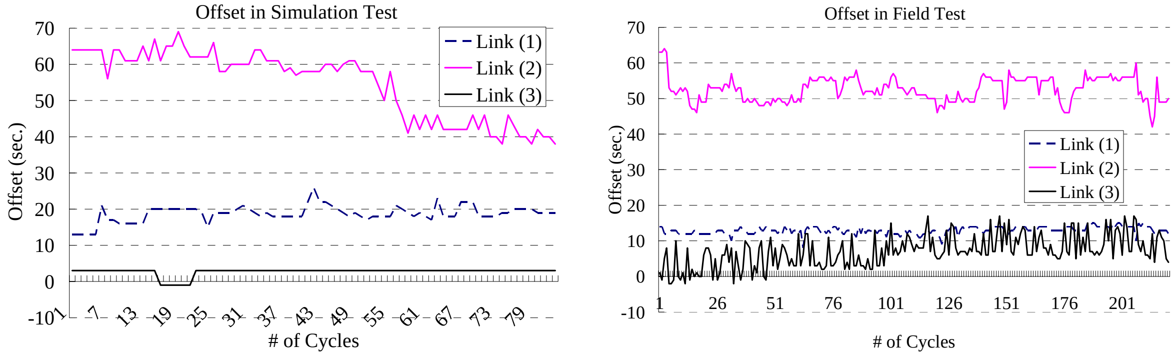


Figure 9 Offset (Left Side is in Simulation Test and Right Side is in Field Test)

CONCLUSIONS

This study improved a traffic signal control CARREN that reduces the network delay measured by ITS technologies by taking into account the stochastic delay. Both simulation and field experiment show that CARREN has good performance to reduce the delay in comparison with the conventional program selection control.

The field test gives us valuable information about future studies. At first, calculation of free flow travel time needs to be improved. Although CARREN can automatically calculate this, it sometimes does not work well because of the effect of other factors, such as inflow vehicles from roadside or pedestrians. Since how to deal with free flow travel time is directly affected to the parameter decision, practical study is needed for this problem.

Sensing errors should be also taken into account for the control. During the field test, the sensors sometimes could not send data. The current system is under assumption that sensors always give sufficient data to CARREN. The reliability in case of data lacking is important for practical use. More discussion about robustness of the control is required.

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