Wide-area Traffic Signal Control Using Predicted Traffic Based on Real-time Information

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Abstract—In this paper, we propose a wide-area traffic signal control using predicted traffic based on real-time information. In conventional studies, the advanced methods of traffic signal control usually require the installation of detectors on all links in the network. As proposed method has an interpolation function, it can be applied to a wide-area road network that includes links on which traffic meters have been not installed. The experimental results using actual traffic data and an actual road map showed that this method is effective at making traffic flow more smoothly.

I. INTRODUCTION

The development of traffic signal control systems is expected to reduce traffic congestion in urban road networks. Recently, it has become possible to obtain real-time traffic information and this is now being provided for route guidance or traffic management. Consequently, a lot of traffic signal control methods based on detected traffic have been proposed by several researchers [1]-[7].

In many cases, traffic signal control methods are evaluated by applying them to traffic simulations [4]. The advantage of using a traffic simulator is that it enables direct observation of the method’s effect on traffic flow. In conventional studies, methods have mainly been evaluated by applying simulations based on restricted road networks and hypothetical traffic volumes [2]. Furthermore, the advanced methods of traffic signal control usually require the installation of detectors on all links in the network [3], [7].

In this paper, we propose a wide-area traffic signal control using predicted traffic based on real-time information. We have already reported a method of interpolating traffic data for roads for which no traffic data is provided [8]. That method was applied to short-term traffic prediction, but its evaluation was insufficient at that time. In this paper, we improve the prediction method and apply it to traffic signal control. The resulting method can be applied to a wide-area road network that includes links that do not have detectors.

In the remainder of this paper, we begin with an overview of this research field. We then describe a method for applying the detected traffic to a wide-area simulation and traffic signal control method based on predicted traffic. Finally, we describe experiments using actual traffic data and an actual road map used in car navigation equipment.

II. OVERVIEW OF RESEARCH FIELD

A. Traffic Simulation

A lot of traffic simulators have been developed to estimate the effect of traffic measures and intelligent transportation systems (ITSs), which reduce traffic congestion and environmental pollution. Teramoto et al. described the use of a traffic simulator to predict traffic conditions for the Nagano Olympic Winter Games [12]. Shiraishi et al. developed a traffic prediction system based on real-time simulation [11]. When a traffic simulator is applied for these purposes, it is important to reproduce the actual traffic conditions in the simulator. For this purpose, detected traffic data is used as the input for simulators.

B. Interpolation of Traffic Data

In Japan, traffic detectors are installed at more than 20,000 locations along principal roads throughout the country. These detectors measure the average travel time of vehicles and the number of vehicles passing through links in 5-minute intervals. This data is collected at a traffic information center and provided to information subscribers in real time. A driver can obtain data for several tens of kilometers ahead of the vehicle’s current location. It is received via onboard car navigation equipment from optical or radio beacons set up along the road. There are currently more than 10 million vehicles in Japan using such traffic data.

Most of the car navigation equipment currently available in Japan uses traffic data for route guidance, but the travel time for links not equipped with detectors is calculated by standard times established beforehand, so congestion on such a link could generate a discrepancy between the actual and computed travel times. A road map of central Tokyo, including 3871 intersections and 11,440 links, is shown in Fig. 1. There are 9763 links without detectors in this area. In Fig. 1, encircled lines indicate the links with detectors. Fig. 2 shows an example of time-series traffic data on a link in Fig. 1 on June 17 (Tuesday) 2003. The vertical axis represents the average speed of vehicles on the link calculated directly from real-time information.

To solve the above-mentioned problems, a method for making spatial interpolations of traffic data must be developed. The method must be able to estimate traffic on links without detectors from the traffic on links with detectors in a wide-area road network. We have proposed a method of interpolating traffic data for roads for which no traffic data is available.
provided by using fuzzy c-means (FCM) [8]. We have also proposed a method of tuning the membership functions using a genetic algorithm [9].

A. Traffic Signal Control

Some of the common traffic signal operations for controlling the traffic flow are cycle time adjustments; split adjustments, where “split” is defined as the fraction of the cycle time allocated to each phase for a set of traffic movements; and offset adjustment, where “offset” is the time difference between the beginning of green phases for continuous traffic movement at successive intersections that may give rise to a “green wave” along an arterial road.

Traffic signal control varies in complexity, from simple systems that use historical data to determine fixed timing plans, to adaptive signal control, which optimizes timing plans for a network of signals according to traffic conditions in real time. Conventional traffic signal control used in Japan, called Program Selection Control, selects optimal signal parameters from predetermined sets to adapt to the current traffic conditions. SCOOT [5], developed in England, and SCATS [6], developed in Australia, are adaptive-cyclic systems, meaning that updates for the signal timing plan are performed at certain time intervals. Other methods based on traffic prediction or real-time simulation have been proposed [3], [7]. These methods usually need traffic data for all the links connected to intersections. However, as explained above, traffic data for links without detectors is not available. In addition to this problem, the methods proposed in conventional studies have usually been evaluated by applying simulations based on restricted road networks and hypothetical traffic volumes [2].

The development plan was as follows.

- We developed a traffic control method that changes parameters according to the traffic conditions of all incoming links predicted by simulation.
- We applied this method to a wide-area network include links on which traffic meters have not been installed by interpolating traffic data for such links using the fuzzy clustering method.
- We evaluated our method by simulation based on an actual road map and actual detected traffic.

III. TRAFFIC SIMULATION BASED ON DETECTED TRAFFIC

A. Vehicle Behavioral Model and Road Network Model

In this model, the relationship between vehicle speed \( V \) and vehicle density \( K \) is defined in equation (1), which is known as the Greenshields formula [10]. Each vehicle is moved according to this relationship. \( K \) is obtained from space headway \( S = 1/K \). \( K_j \) and \( V_f \) denote the jam density and free speed, respectively, where free speed is the road’s speed limit. This calculation of vehicle movements is performed for all vehicles at intervals of one second.

\[
V = V_f \left(1 - \frac{K}{K_j}\right) \quad (1)
\]

Our simulator uses map databases in the standard format developed and established by the Navigation System Researchers’ Association in Japan. The maps used in actual car navigation equipment are of this type and they can indicate areas where spontaneous traffic congestion occurs. This simulator is capable of simulating any road in Japan. The map includes indicators of road characteristics such as speed limit, length, road class, number of lanes, and the existence of traffic lights.

We need algorithms that can determine the phases that are combinations of links given the right of way at same time because the map indicates only the existence of signals. Our idea for such an algorithm is shown below.

(i) Three-road intersection

Step 1: calculate the difference in direction of two of the roads.

Step 2: select two roads for which the absolute value of the difference is close to 16.

Step 3: let the two roads be one group and let the other road be another group.

(ii) Four-road intersection

Step 1: sort the roads according to the direction in descending order.
Step 2: let the 1st and 3rd be one group. 
Step 3: let the 2nd and 4th be another group. 

When the number of crossing roads is an odd number greater than 3, we decide the combination of signals by appropriately extending (i). Likewise, to decide the signal combinations for an even number of crossing roads greater than four, we extend (ii).

B. Adjustment of Traffic Distribution in the Simulator

With the aim of reflecting detected traffic data in a traffic simulator, we first present a method for calculating link traffic density $K$ (number of vehicles per kilometer) from average vehicle speed $V$ calculated by (1). Here, we use the following empirical formula as an amendment to (1).

$$K_D = \begin{cases} 
K_J \times 0.6 & \text{for } V = 0 \\
K_J \times (1 - V / V_F) & \text{for } 0 < V < V_F \\
K_J \times 0.02 & \text{for } V = V_F 
\end{cases} \quad (2)$$

We determined this equation empirically because the simulator is to be applied to a wide-area road network. The subscript in $K_D$ indicates traffic density calculated from detected traffic data.

To reduce the prediction error that arises after running the traffic simulator, we correct the traffic density obtained from (2) by using detected traffic data from the next time interval. Here, a link on which traffic meters have been installed is referred to as a “metered link” and a link having no meters is referred to as an “ordinary link.” For metered links, we simply use traffic density $K_D$ as calculated from (2), but for ordinary links, we correct the traffic density according to the following formula by using interpolated data usage rate $r$ ∈ [0, 1].

$$K = rK_{ECM} + (1 - r)K_{Sim}, \quad (3)$$

where $K$ is the traffic density after correction, $K_{ECM}$ is the traffic density calculated from the speed interpolated by FCM, and $K_{Sim}$ is the traffic density obtained by simulation. An optimal value for $r$ is determined by experiment.

The procedure for generating traffic is given below. The distribution of traffic flow in the simulator should approach that of the actual traffic flow after repeating steps 6 to 8.

Step 1: Input map data and current traffic data for the target road network.
Step 2: Calculate the average speed of vehicles on all metered links on the map directly from detected data.
Step 3: Calculate the average speed of vehicles on all ordinary links on the map using FCM.
Step 4: Calculate the traffic density on all links on the map using (2).
Step 5: Begin the traffic flow simulation.
Step 6: Input detected traffic data from the next time interval.
Step 7: Calculate the traffic density on metered links using (2) and that on ordinary links using (3).
Step 8: Jump to step 6 unless the current number of loops has reached a certain value.

IV. TRAFFIC SIGNAL CONTROL

A. Parameter Modification Based on Real-time Detected Traffic

In this method, signal control parameters are determined based on the degree of congestion for each phase every 5 minutes when traffic data is obtained. On this occasion, we made the assumption that only splits are decided by this method, so other parameters are fixed or not considered. The congestion degree of phase $i$ at time $t$ is defined as

$$X_i(t) = \max_{j \in S_i} \left[ 1 - \frac{v_j(t)}{V_F} \right], \quad (4)$$

where $S_i$ is the set of links belonging to phase $i$, $V_j$ is the free speed of link $j$, and $v_j(t)$ is the average speed of link $j$ at time $t$ calculated from detected traffic data. The splits for phase $i$ at time $t$ are then determined as

$$g_i(t) = \frac{G_i + d_i(t)}{\sum_{k=1}^{n} (G_k + d_k(t))}, \quad (5)$$

where $G_i$ is the normal split of phase $k$ and $d_i(t)$ is the relative congestion degree of phase $i$ at time $t$ that can be calculated by

$$d_i(t) = \frac{X_i(t) - \alpha}{\sum_{k=1}^{n} X_k(t)}, \quad (6)$$

where $\alpha$ is a coefficient for adjusting the splits by increasing or decreasing them.

B. Parameter Modification Based on Predicted Traffic

Next, we describe a method that adjusts parameters based on predicted traffic data. At the beginning of a predictive simulation, the present traffic condition is generated by the adjustment simulation using traffic data up to the present. In the prediction sim, the average speed of vehicles passing though a link is observed on metered links every 5 minutes. The splits for phase $i$ at time $t$, $g_i(t)$, are then determined by (5) using this predicted traffic data. In this case, however, $d_i(t)$ is calculated by

$$d_i(t) = \frac{X_i(t) + \hat{X}_i(t)}{\sum_{k=1}^{n} (X_k(t) + \hat{X}_k(t))} \times \alpha, \quad (7)$$

where $\hat{X}_i(t)$ is the future congestion degree of phase $i$ calculated by

$$\hat{X}_i(t) = \beta \times \sum_{u=t+1}^{T} X_i(u), \quad (8)$$

where $\beta$ is the usage rate of predicted traffic data and $T$ is the number of predicted traffic data values used for calculating $\hat{X}_i(t)$.

V. EXPERIMENT

A. Evaluation of Predictive Simulation Accuracy

(1) Experimental Method
To evaluate the accuracy of traffic prediction by our
simulation, we forecast the average speed of vehicles on links in central Tokyo on June 16 (Monday) to 22 (Sunday), 2003 for up to 30 minutes ahead. We compared the obtained results with the results by the nearest neighborhood method. That method has been widely used in traffic prediction of wide-area network in Japan, because it's computational cost is low and there is a large amount of historical traffic data.

Note that here the link targeted for prediction was a metered link, and while we did not, of course, use detected traffic data for that link in the experiment, we did treat that data as true values for evaluating prediction results. The target map included 3781 intersections, 11,440 links, and 2924 metered links. As experimental conditions, we set \( r \) in (3) to 0.4 and the maximum loop number in step 8 to 8, we used 6 month’s worth of historical detected traffic data as search data for the nearest neighborhood method, and we set the number of neighborhoods to 12.

Predictions were made for 6 5-minute intervals into the future, i.e., for up to 30 minutes ahead. We selected 50 target cases having clear patterns of congestion outbreak, congestion dissolution, heavy congestion, or no congestion for ordinary roads.

(2) Experimental results

The experimental results are shown in Figs. 3 to 6. In each of these figures, the horizontal axis represents the prediction period (in 5-minute intervals into the future) and the vertical axis represents the absolute error of the difference (km/h) between the actual speed calculated directly from detected traffic data and that observed in the simulation. The results in Figs. 3 to 6 correspond to times of congestion outbreak, congestion dissolution, heavy congestion, and no congestion, respectively.

The results shown in these figures reveal the following. In Figs. 3 and 4, the absolute errors in speed obtained by simulation are lower than those obtained by the nearest neighborhood method at almost all points in time. In both of these cases, our method is superior to the nearest neighborhood method. Next, in Figs. 5 and 6, the absolute errors in speed obtained by simulation are higher than those obtained by the nearest neighborhood method at almost all points of time. However, both of these methods had fewer or as many 10-km/h errors throughout the entire prediction period.

Whereas the nearest neighborhood method does not consider the traffic conditions of neighboring roads, the simulator treats the inflow and outflow of vehicles to and from the target link. Therefore, traffic prediction by simulation is superior when the change in vehicle speed is large such as at congestion outbreak or dissolution congestion.
found that: vehicles, and the horizontal axis shows the time of day. We obtained results. The experimental results were evaluated in terms of the average speed of all the vehicles. D+I, and D+I+P) to evaluation simulations and compared the is extended by 5 s. intersection, the length of the green phase covering that road was 90 s (green: 40, yellow: 3, all red: 2). If a principal road (national road or principal local road) connects into an traffic data in the time range from 7:00 am to 10:00 am from June 16 (Monday) to 18 (Wednesday) 2003. As experimental conditions, $\alpha$ in (6) was set to 0.5, $\beta$ in (8) was set to 0.25, and $\alpha$ in (8) was set to 4. The cycle time of standard intersections was 90 s (green: 40, yellow: 3, all red: 2). If a principal road (national road or principal local road) connects into an intersection, the length of the green phase covering that road is extended by 5 s.

We applied four traffic signal control methods (Fixed, D, D+I, and D+I+P) to evaluation simulations and compared the obtained results. The experimental results were evaluated in terms of the average speed of all the vehicles.

B. Evaluation of Traffic Signal Control

(1) Experimental Method

To evaluate the effectiveness of interpolation and prediction in traffic signal control, we performed traffic signal control experiments for an actual road network. We used the same road map as used in section 4, and we used traffic data in the time range from 7:00 am to 10:00 am from June 16 (Monday) to 18 (Wednesday) 2003. As experimental conditions, $\alpha$ in (6) was set to 0.5, $\beta$ in (8) was set to 0.25, and $\alpha$ in (8) was set to 4. The cycle time of standard intersections was 90 s (green: 40, yellow: 3, all red: 2). If a principal road (national road or principal local road) connects into an intersection, the length of the green phase covering that road is extended by 5 s.

We applied four traffic signal control methods (Fixed, D, D+I, and D+I+P) to evaluation simulations and compared the obtained results. The experimental results were evaluated in terms of the average speed of all the vehicles.

(2) Experimental Results

The experimental results are shown in Fig. 7 and Table I. In Fig. 7, the vertical axis represents the average speed of all vehicles, and the horizontal axis shows the time of day. We found:

- Fixed gave the lowest average speed among the methods through the entire region.
- The average speeds of D+I and D+I+P were both higher than that of D through the entire region.

The total average speeds for each method and the increase compared with Fixed are shown in Table I. In this table, D+I+P gave the highest average speed among the methods, with a 9.1% increase compared with Fixed. This means that our method is effective at making traffic flow more smoothly. But it was only slightly better than D+I. We have not yet considered the utilization of predicted traffic in this instance, so it is necessary for us to improve our method.

VI. Conclusion

In this paper, we proposed a wide-area traffic signal control using predicted traffic based on real-time information. As this method has an interpolation function, it can be applied to a wide-area road network that includes links on which traffic meters have been not installed. The experimental results using actual traffic data and an actual road map showed that the predictive accuracy of this method is superior to that of the nearest neighborhood method at times of congestion outbreak and dissolution and that this method is effective at making traffic flow more smoothly. In future research, this technique should be further evaluated for a variety of maps, dates, days of the week, and time slots. We will extend it so that traffic congestion can be further reduced.

**REFERENCES**

