Travel Time Prediction on Inter-Urban Expressways Based on Uplink Information from Vehicles to DSRC beacons

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This paper describes a method of travel time prediction for inter-urban expressways using uplink information from equipped vehicles with on-board ETC unit. Uplink information, which contains vehicle's ID and data transmission time, is collected at a beacon installed on roadside and matched with another uplink information at the adjacent beacon to measure the travel time of the vehicle (uplink travel time). Uplink travel time would be more fundamental than the conventional travel time information estimated by loop detector speed, but it will be inaccurate when a queue is found on the expressway because of the measurement delay. Therefore, it must be followed by an appropriate prediction method to compensate the measurement delay. In this paper, the way of uplink travel time measurement is outlined at first. Then, the prediction method based on cumulative traffic flow diagram is explained. Finally, the proposed method is applied for the travel time prediction on the Kyushu Expressway and validated its advantage by comparing with conventional travel time information.

Keywords: *travel time prediction, expressway, telematics, uplink, ETC, DSRC.*

1. Introduction

Nowadays the electric toll collection (ETC) system is rapidly penetrated in Japan. The penetration rate of the equipped vehicles with on-board ETC unit is close to 80% of the whole vehicles running on expressways[1]. Since ETC on-board unit has the capability to transmit uplink information containing vehicle ID to roadside DSRC (dedicated for short range communication) beacon as well as the time stamp at its transmission. The travel time of each equipped vehicle can be measured by subtracting the time stamp of two matched uplink information of the same vehicle collected at adjacent beacons.

Travel time information using uplink (uplink travel time) is noticed with the following advantages to the conventional travel time measurement using loop detectors.

- Travel time measurement using uplink is more direct and hence would be more fundamental than using loop detectors.
- The implementation and the maintenance of uplink travel time measurement system is less costly than the system using loop detectors.

As loop detectors measure point speeds of passing vehicles, they are required to install with relatively short interval on expressways in order to estimate section travel time with sufficient accuracy. On the major inter-urban expressway sections in Japan, loop detectors are normally installed approximately at every 2 kilometers whereas the average distance between adjacent interchanges is about 15 to 20 kilometers.

On the other hand, uplink travel time directly measures the section travel time with less number of sensors which are installed only at the section immediately downstream of each interchange. As DSRC beacons can communicate with vehicles from roadside position, their installation and maintenance are quite easier and less costly than loop detectors buried beneath the pavement.

There is, however, a problem in the uplink travel time measurement. As the travel time of each vehicle is determined only at the time when the vehicle passes the downstream end of the subject section, the uplink travel time involves delay by the queue, and it may be inaccurate when the traffic condition changes by time[2]. Assume that some equipped vehicles just have passed by the beacon at the downstream end of the subject section. Even though the uplink travel time is given by averaging the travel times of those equipped vehicles, it may not be correct for the vehicles currently arriving at the upstream end. Because the traffic condition will not be the same after some time when those arriving vehicles reach to the tail of the congested section.

It is, therefore, necessary that the uplink travel time is compensated such measurement delay by "short term" travel time prediction technique. In chapter 2, the prediction method for uplink travel time is described after the literature survey on existing travel time prediction methods. The prediction method proposed here uses "cumulative traffic flow diagram" and predicts

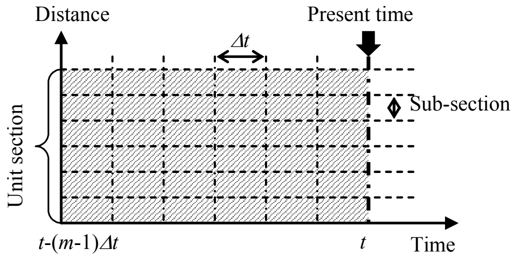

Fig. 1 Available traffic conditions in time-space for the conventional prediction methods.

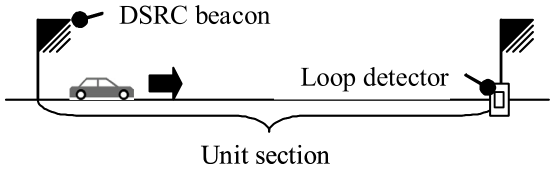

Fig. 2 Sensor arrangement of uplink travel time prediction

traffic flows at both upstream and downstream ends, instead of predicting travel time directly. The reason to use such diagram is explained as well as pros and cons of the proposed method.

In chapter 3 followed by the conclusion, the uplink travel time prediction method is applied to the Kyushu Expressway, where a pilot experiment of the uplink travel time measurement was conducted, for validation. The accuracy of the predicted uplink travel time is to be compared with the conventional travel time estimated by loop detector speeds.

2. Travel time prediction using uplink

2.1. Survey on existing prediction methods

So far, number of studies on short term travel time prediction methods are found in literature. Pattern matching method[3][4][5] is frequently used. It searches the traffic conditions similar to today's condition from historical database and assumes the hereafter will be the same as those historical data. Although there is less theoretical support for the pattern matching approach, it is regarded practically valid for ordinary traffic conditions.

With more theoretical support, time series data analysis techniques such as auto-regression model[6][7], neural network computing[8][9], cross-correlation[10], etc. are to be applied for the prediction. Those techniques seem to have essentially the same applicability, because they depend on the recurrence in daily traffic conditions. State-space models like Kalman filter and its variations are to be combined with those time series data modeling approaches, in order to compensate stochastic errors in sensor data or to complement missing data[11][12].

Most of those methods deal with "sub-sections" of which lengths are relatively shorter than the subject section. It is a premise that the traffic status of each sub-section is available up to the present time. Thus, those methods are formulated as following mapping form.

$$\boldsymbol{F} : \left\{ s_i(t - j\Delta t) \to \overline{T}(t) \mid i \in \boldsymbol{I}, j = 0, \ldots, m-1 \right\} \quad (1)$$

where,

- $\overline{T}(t)$: predicted travel time at time t.
- Δt : update interval of travel time information (5 minutes).
- $\boldsymbol{I}$: set of the sub-sections included in the subject section.
- $s_i(t)$: traffic status of i-th sub-section at time t in terms of either speed, flow or density.
- m : positive number.

Here, $\boldsymbol{F}$ means any explicit or implicit mapping function from the traffic statuses of sub-sections to travel time information, and formulation (1) is to be illustrated as Fig. 1 that means the traffic status of the hatched area is used for the prediction.

2.2. Sensor arrangement for the prediction

Fig. 2 illustrates the ideal sensor arrangement for the uplink travel time prediction. Two DSRC beacons are installed at the both ends of the subject section, which will be an adjacent interchange pair section. Let us here call the subject section as "unit section". At the downstream end, a loop detector will be installed to measure the cumulative departure traffic counts from the unit section. The usage of the cumulative traffic counts will be explained in section 2.4.

2.3. Nature of uplink travel time

Uplink travel time is an average value of the travel times of equipped vehicles passing at the downstream end of unit section. It is given by the following equation.

$$T^D(t) = \frac{1}{\left| \boldsymbol{J}^D_{t-\Delta t,t} \right|} \sum_{j \in \boldsymbol{J}^D_{t-\Delta t,t}} (t_j^D - t_j^U) \quad (2)$$

where,

- $T^D(t)$: departure based uplink travel time at time t.
- $\boldsymbol{J}^D_{t-\Delta t,t}$: set of the equipped vehicles departing from the downstream end of the unit section from t-Δt to t.
- t_j^D : time stamp of j-th vehicle's uplink collected at the downstream beacon.
- t_j^U : time stamp of j-th vehicle's uplink collected at the upstream beacon.

Here, 't_j^D - t_j^U' is a direct measurement of individual travel time of the j-th equipped vehicle, while a conventional prediction method formulated as (1) does 'estimate' the travel time from the traffic statuses of sub-sections. In this sense, uplink travel time is more fundamental than the conventional methods.

On the other hand, the ideal travel time to be provided to the vehicles arriving at the upstream section is defined as following equation.

$$T^A(t) = \frac{1}{\left|\boldsymbol{J}^A_{t-\Delta t,t}\right|} \sum_{j \in \boldsymbol{J}^A_{t-\Delta t,t}} (t^D_j - t^U_j) \tag{3}$$

where,

$T^A(t)$: arrival based ideal travel time at time t.

$\boldsymbol{J}^A_{t-\Delta t,t}$: set of the whole vehicles arriving at the upstream end from t-Δt to t.

If we assume almost the same travel speed for the vehicles in $\boldsymbol{J}^A_{t-\Delta t,t}$, the following relationship can be found between the ideal travel time and departure based uplink travel time.

$$T^A(t - T^D(t)) \cong T^D(t) \tag{4}$$

This means uplink travel time is ideal travel time information but always delayed by $T^D(t)$ and it is to be compensated by some prediction method.

2.4. Prediction based on cumulative flow diagram

Fig. 3 shows the available traffic conditions in time-space for the uplink travel time prediction by the hatched area. Different from Fig. 1, we do not deal with sub-sections and the hatched area loses the latest information which is necessary for the conventional prediction methods.

Taking considerations for those differences, the travel time prediction method using cumulative flow diagram is proposed. The method consists of the following procedure illustrated in Fig. 4.

1) Draw the curve $D(t)$ of the cumulative traffic flow for the departure vehicles up to the present time t_0 by using the detector information installed at the downstream end of the unit section.
2) For every $\{t_i, \mid i=-m+1, ..., 0\}$ marked by white dots with the interval Δt, take the black dots offset to the left (= past) as much as the uplink travel time $T^D(t_i)$.
3) Draw the curve $A(t)$ of the cumulative traffic flow for the arrival vehicles by joining the black dots until the time t_0 - $T^D(t_0)$.
4) Extend the curve $A(t)$ to the present time as the dotted line by predicting the traffic flow from t_0 - $T^D(t_0)$ to t_0.
5) Extend the curve $D(t)$ as well, up to the same height of the extended the curve $A(t)$. The distance between the two curves at this height provides the arrival based 'predicted' travel time $\hat{T}^A(t_0)$. (Hereafter, hut (^) means an estimated value in contrast of an observed value.)

The procedure described above treats the traffic passing through the downstream section of the unit section with a first-in-first-out (FIFO) queue which is a natural modeling of uplink travel time. It is clear that we can obtain the predicted travel time at any future time by extending the curve $A(t)$ to the desired time. The prediction method for the traffic volume used in the step 4) and 5) will be explained in section 2.5.

Here, $D(t)$ is a measured volume by loop detector but $A(t)$ is just a calculated volume. The reason why we do not measure it by the detector installed at the upstream end is that we should allow the following situation in reality to retain the FIFO assumption.

- There is sometimes on/off ramps at somewhere middle in the unit section.
- The traffic count by each detector may include individual error which may cause inconsistency in the FIFO assumption.

As an additional feature, we may expect the adaptability for incident for the prediction method using cumulative flow diagram. An incident may cause subsequent traffic jam of which is often extraordinary. Prediction in such situation is not easy for any conventional method based on historical data. We may, however, operate the cumulative flow diagram to fit the incident imposing the modified cumulative departure flow curve to consider the capacity reduction by the lane closure. Although we leave the validation of this operation as a future task and we recognize the issues on how to estimate the incident duration, the possibility of the adaptation for incidents could be a support for the prediction method using cumulative flow diagram.

2.5. Traffic flow prediction with ARMA model

There are number of techniques to predict future traffic flows from historical database. We have, so far,

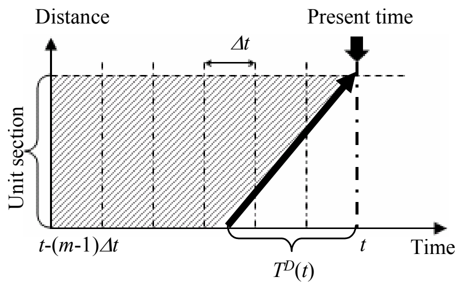

Fig. 3 Available traffic conditions in time-space for the uplink travel time prediction.

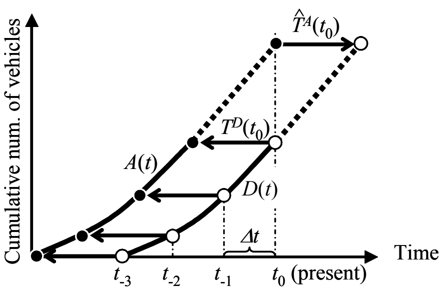

Fig. 4 Travel time prediction using cumulative flow diagram.

studied about the pattern matching[13] and the time series data analysis with ARMA (auto-regression with moving average) model[14]. For the prediction method described in this paper, the latter was adopted because of the advantage in the accuracy to the former.

ARMA model is formulated as following equations.

$$\begin{cases} x_i = \dfrac{1}{n}\sum_{j=0}^{n-1} y_{i-j} \\ x_1 = \sum_{i=0}^{m-1} a_i x_{-i} \end{cases} \tag{5}$$

where,

- y_i : observed 'raw' data at i-th time slot.
- x_i : smoothed data at i-th time slot.
- n : width of moving average.
- m : size of the time series data.
- a_i : auto-regression (AR) coefficients.

As to the suffix i, '0' means the present and negative value means the past time. If we want to get the future time series data for $i \geq 1$, we may repeatedly apply the second equation of (5).

The values at every 5 minutes for both departure and arrival traffic flows could be treated as time series data, and ARMA model is individually applied for each of them. Here, n=3, i.e. 15 minutes moving average, is used to remove the short fluctuations in traffic flow data. The size of the time series data m is optimized by minimizing AIC[15] (Akaike information criterion). Once m is determined, AR coefficients a_i can be calculated by Yule-walker algorithm[15].

Since AR model is based on a liner function, it is obvious the non-linearity in the traffic flow will affect the accuracy of the prediction. One of the major non-linearity in traffic flow would be daily changes. In order to remove those daily changes, AR model is identified for the difference from the average flow pattern to be prepared for each of the day from the traffic flow data. Therefore, the first equation in (5) is modified as follows.

$$x_i^D = \frac{1}{n}\sum_{j=0}^{n-1} q_{i-j,w}^D - \overline{q}_{iw}^D \tag{6}$$

$$x_i^A = \frac{1}{n}\sum_{j=0}^{n-1} q_{i-j,w}^A - \overline{q}_{iw}^A \tag{7}$$

where,

- x_i^D, x_i^A : the subtracted flows for the departure (D) and the arrival (A) traffic.
- q^D_{iw}, q^A_{iw} : the flows at i-th time slot of w-th day of the week.
- $\overline{q}_{iw}^D, \overline{q}_{iw}^A$: the average flows at i-th time slot of w-th day of the week.

Those average flow patterns should be periodically updated to adapt the monthly or the seasonal changes in traffic. For an instance, they would be updated with the recent one month data for every week.

2.6. Travel time prediction for an O-D pair

In the implementation of the uplink travel time prediction method, a unit section will be assumed as an adjacent interchange pair as shown in Fig. 2. However, the predicted travel time will be required for an arbitrary interchange O-D (origin-to-destination) pair consisting of several unit sections. In such case, the predicted travel time of each unit section will be accumulated from origin interchange r to destination s ($r < s$) according to time-slicing method defined as the following formula.

$$\hat{T}_{rs}(t) = \begin{cases} \hat{T}_{rs}^A(t) & \cdots (r+1=s) \\ \hat{T}_{rs-1}(t) + \hat{T}_{s-1s}^A(t + \hat{T}_{rs-1}(t)) & \cdots (r+1<s) \end{cases} \tag{8}$$

where,

$\hat{T}_{rs}(t)$: predicted travel time at time t from r to s.

3. Validation of uplink travel time prediction

3.1. Field experiment on the Kyushu Expressway

For the purpose of validation, the uplink travel time prediction method was applied to the Kyushu Expressway, where the DSRC uplink travel time measurement was experimented in the section from Dazaifu IC to Ueki IC. As shown in Fig. 5, there are 9 interchanges and DSRC beacons for each direction. Although each beacon is not exactly installed at the interchange position but in the middle of the interchanges, we regarded the adjacent beacon pair as a unit section.

The uplink travel times were collected in August

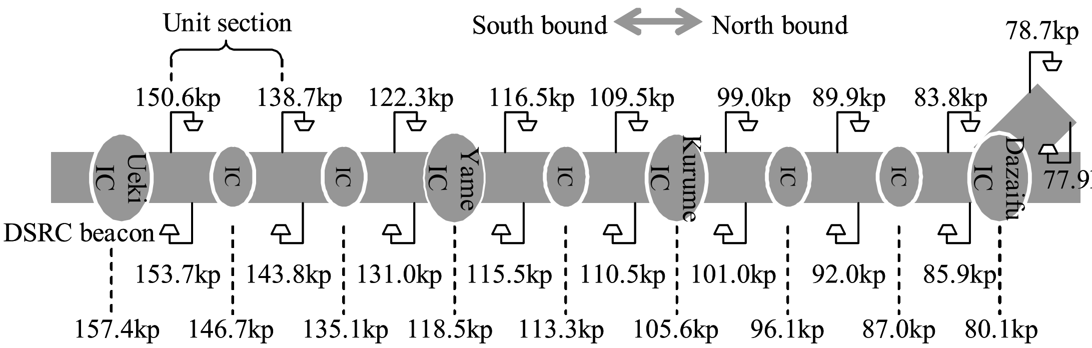

Fig. 5 Arrangement of DSRC beacons and interchanges on the Kyushu Expressway for the validation.

2006. We have prepared the average flow patterns for weekdays, Saturdays and holidays.

On some holidays, traffic congestions were found for the north bound direction heading to Dazaifu IC. On such days, for an instance, the drivers departing from Ueki IC, where is 77 km south to Dazaifu IC, are to be provided the travel time predicting the congestion in about 50 minute future.

3.2. Travel time information to be compared

For the purpose of the validation, predicted uplink travel time (PredUTT) which is explained in the previous chapter has been compared with three different travel time information as follows.

3.2.1 Time-slicing travel time (as true value)

Time-slicing travel time (TmsTT) is assumed as the actual travel time that took for the driver arriving at the origin interchange at time t. This is calculated with equation (8), but the 'measured' arrival based uplink travel times are used instead of the predicted uplink travel time.

$$T_{rs}(t) = \begin{cases} T_{rs}^{A}(t) & \cdots (r+1=s) \\ T_{rs-1}(t) + T_{s-1s}^{A}(t + T_{rs-1}(t)) & \cdots (r+1<s) \end{cases} \quad (9)$$

where,

$T_{rs}(t)$: TmsTT at time t from r to s.

3.2.2 Instantaneous uplink travel time

Instantaneous uplink travel time data (InstUTT) is a simple summation of the measured arrival based uplink travel times of the unit sections in the experiment section. InstUTT is given by the following equation.

$$T_{rs}^{\#}(t) = \sum_{k=r}^{s} T_{k}^{D}(t) \quad (10)$$

where,

$T^{\#}_{rs}(t)$: InstUTT at time t from r to s.

T^{D}_{k} : departure based uplink travel time of k-th unit section at time t.

3.2.3 Instantaneous detector travel time

There is also conventional travel time information system using loop detectors for the experiment section on the expressway. Those detectors are installed on each lane at approximately every two kilometers. The experiment section is divided into the sub-sections of which one detector in the middle represents the traffic condition. The section travel time estimated with the volume-weighted harmonic mean speed over each lane of the sub-section is calculated as follows for the purpose of the comparison (InstDTT).

$$T_{sr}^{*}(t) = \sum_{h \in [r,s]} \frac{l_h}{\max(v_h(t), v_{\min})} \quad (11)$$

where,

$T^{*}_{sr}(t)$: InstDTT at time t from s to r.

l_h : the length of the sub-section covered by detector h within the unit sections from r to s.

$v_h(t)$: the volume-weighted harmonic mean speed at time t in sub-section h.

$v_{\min}$: minimum threshold speed to avoid zero division ($v_{\min}$ = 2 [km/hr] in this study).

3.3. Validation with 'hitting ratio'

In order to evaluate the accuracy of travel time information, here we use the 'hitting ratio' which means the percentage of the number of times at which the travel time information is within the allowable range of TmsTT. The width of the allowable range is given by Table 1. This is the strict version of the range from the survey for the expressway users[16], which says more than 50% of the drivers may accept the error in travel time information. Here, the lower bound of the allowable range is set to the half of the upper bound, according to the idea that the under-estimation of travel time might be more intolerant for drivers' satisfaction than the over-estimation.

Fig. 6 shows the comparison of the hitting ratios of InstUTT, InstDTT and PredUTT for the different distance to Dazaifu IC. For every distance, both InstUTT and PredUTT show higher hitting ratio than InstDTT. PredUTT slightly improves the accuracy to InstUTT and the improvement becomes larger for longer

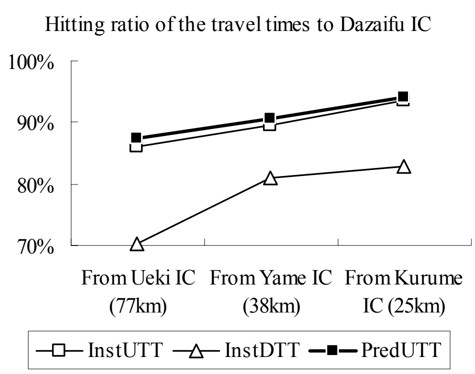

Fig. 6 Comparison of the hitting ratio

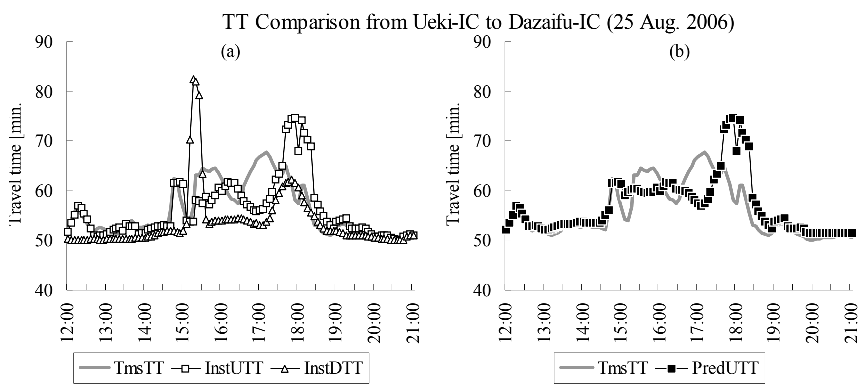

Fig. 7 Comparison of travel times for a congested day.

distance.

Fig. 7 illustrates the travel time comparison for a congested day as an example. On this day, the congestion started at around 14:30 and lasted until 18:30. PredUTT quickly responds as TmsTT increasing at the beginning of the congested period rather than InstUTT and InstDTT. Although there are errors with over-estimated PredUTT at around 18:00 when the congestion is getting clear, it might be found that PredUTT generally takes advantage than InstDTT.

Table 1 Allowable range for hitting ratio.

T_{rs}: TmsTT	Allowable range in this study		Allowable range from survey result[16]
	Upper	Lower	
$0 \le T_{rs} < 30$	$T_{rs}+5$	$T_{rs}-2.5$	$T_{rs} \pm 10$
$30 \le T_{rs} < 60$	$T_{rs}+10$	$T_{rs}-5.0$	$T_{rs} \pm 15$
$60 \le T_{rs} < 120$	$T_{rs}+15$	$T_{rs}-7.5$	$T_{rs} \pm 20$
$120 \le T_{rs}$	$T_{rs}+20$	$T_{rs}-10$	$T_{rs} \pm 30$

4. Conclusions

In this paper, the travel time prediction method using uplink information was proposed. Travel time measurement using uplink can be considered as more fundamental and less costly than the conventional measurement with loop detectors. The prediction method estimates the travel time with the cumulative flow diagram of the section between neighboring interchange pair as a unit section, which seems a natural modeling of the traffic condition for the section with the cumulative flow at the downstream end and the departure based travel time measured by uplink information. The accuracy of the predicted travel time with the proposed method was validated by applying to the DSRC uplink data which was collected through the experiment on the Kyushu Expressway. The comparison of ‘hitting ratio’ may conclude that the predicted uplink travel time takes advantage to the travel time with conventional loop detector information.

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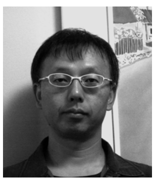

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