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An Estimation of Link Travel Time in Urban Road Networks

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Abstract — **The travel time is one of the most valuable traffic information among drivers because of playing an important role as the basis for dynamic route guidance system. The dynamic route guidance system is effective to reduce the congestion in urban road networks. This paper describes the analysis, measurement and estimation of link travel time by taking into account the traffic flow dynamics, signal control parameters and starting delay. Link travel time are simulated for a traffic network before and during rush hours in Fukuyama city, Japan.**

Keywords – link travel time, traffic flow dynamics, test-car technique, estimation

I. INTRODUCTION

The travel time is a measure of traffic flows in traffic networks and indispensable information for drivers. The marginal travel time on a link is obtained using a function of number of vehicles on a link at time t [1].The travel time is predicted by AR model and statistical model [2] along arterials in Aomori city, Japan. The estimation of link travel time by the fuzzy neural network is more accurate than the fuzzy expert system model [3]. The analysis and estimation of travel time are required for any routes including the right-turn and the left-turn. This paper studies the analysis of the mean link travel time for any routes based on the traffic flow dynamics, signal control parameters and moving direction of vehicles at downstream signalized intersections in urban road networks. The link travel time are measured by the average rate of speed of the traffic stream in the urban traffic network for Fukuyama city, Japan before and during rush hours. The measurement values of the link travel time are compared with the estimation values about two routes in Fukuyama city.

II. ANALYSIS OF TRAFFIC FLOW DYNAMICS

The volume balance of each lane at each signalized intersection in the traffic network is shown in Fig.1 and written by

$$\begin{aligned} x_e(i,j,m,k) &= x_e(i,j,m,k-1) \\ &\quad + x_i(i,j,m,k) - x_o(i,j,m,k) \end{aligned} \tag{1}$$

$$\begin{cases} x_o(i,j,m,k) = \xi(i,j,m,k)\cdot c_x(i,j,m,k) \\ x_e(i,j,m,k) \ge 0 \end{cases} \tag{2}$$

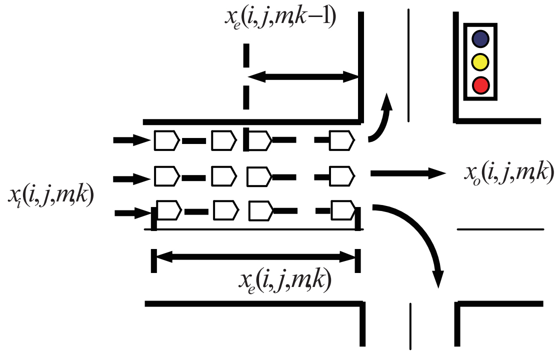

Figure1. Volume balance for each lane at each signalized intersection.

Traffic Flow Dynamics	Offset Control	Moving Direction at Downstream Signalized Intersection
Non-congestion	Control	Straightaway Right-turn Left-turn
	Non-control	Straightaway Right-turn Left-turn
Congestion		Straightaway Right-turn Left-turn

Figure2. Classification for analysis of mean link travel time.

where i, j and m denote the location of each signalized intersection and the approach of vehicles respectively. Time is shown by $k=k\Delta T$ with sampling time ΔT, which is equally set to the cycle length. $x_e(i,j,m,k)$, $x_i(i,j,m,k)$ and $x_o(i,j,m,k)$ denote the excess incoming volume, incoming volume and outgoing volume. $\xi(i,j,m,k)$ is evaluated by taking the value of dividing the outgoing volume $x_o(i,j,m,k)$ by the capacity $c_x(i,j,m,k)$ under any traffic flow conditions.

In the volume balance at each signalized intersection, it is assumed that the incoming volume $x_i(i,j,m,k)$ is measured by detectors and the outgoing volume $x_o(i,j,m,k)$ is controlled by the three signal control parameters at the signalized intersection concerned

$$\begin{aligned} &x_o(i,j,m,k) = \\ &f\left[c_y(i,j,m,k), r_g(i,j,m,k), t_{off}(i,j,m,k)\right] \end{aligned} \tag{3}$$

TABLE I. NOTATION

T_r, t_{run}	Link running time
T_s	Link stopping time
P_s	Stopping rate at the downstream signalized intersection
t_g	Green time
t_y	Yellow time
t_r	Red time
P_g	Probability of green time
P_y	Probability of yellow time
P_r	Probability of red time
t_{dr}	Time difference of green initiation between straightaway and right-turn directions
t_{dl}	Time difference of green initiation between straightaway and left-turn directions
t_{cs}	Outgoing time of straightaway lane queue
t_{cr}	Outgoing time of right-turn lane queue
t_{cl}	Outgoing time of left-turn lane queue
y_s	Queue length of straightaway lane
y_r	Queue length of right-turn lane
y_l	Queue length of left-turn lane
t_s	Starting delay
φ_s	Saturation flow on the approach of straightaway lane at the downstream signalized intersection
φ_r	Saturation flow on the approach of right-turn lane at the downstream signalized intersection
φ_1	Saturation flow on the approach of left-turn lane at the downstream signalized intersection
d	Link length
v	Running speed of straightaway lane
α_r	Probability of non-passing through the right-turn lane at the downstream signalized intersection
α_l	Probability of non-passing through the left-turn lane at the downstream signalized intersection

where $c_y(i,j,m,k)$, $r_g(i,j,m,k)$ and $t_{off}(i,j,m,k)$ denote the cycle length, green split and offset respectively. The control input $u(i,j,m,k)$ is defined by

$$u(i,j,m,k) \triangleq f\left[c_y(i,j,m,k), r_g(i,j,m,k), t_{off}(i,j,m,k)\right] \tag{4}$$

The traffic flow dynamics under the signal control is then written by

$$\begin{cases} x_e(i,j,m,k) = x_e(i,j,m,k-1) \\ \qquad + x_i(i,j,m,k) - u(i,j,m,k) \\ y_c(i,j,m,k) = l_m(i,j,m,k) \cdot x_e(i,j,m,k) \end{cases} \tag{5}$$

where the upper limit of the control input is determined by Eq.(2). The incoming volume in case of the congestion $x'_i(i,j,m,k)$ equals to $x_e(i,j,m,k\text{-}1)+x_i(i,j,m,k)$. The observation equation of the congestion length $y_c(i,j,m,k)$ is described in such a way that the state variable is multiplied by a "transformation factor" $l_m(i,j,m,k)$, which means the average head distance of queueing vehicles.

III. ANALYSIS OF LINK TRAVEL TIME

The mean link travel time of urban road networks are analyzed by taking the traffic flow dynamics, offset control and moving direction of vehicles at downstream signalized intersections into account in this paper. The mean link travel time consisting of the running time and the stopping time are analyzed according to the classification of Fig.2. It is assumed that the three signal control parameters consisting of the cycle length, green split and offset are controlled optimally using a signal control algorithm [4].

A. In the Case of Non-congestion at the Downstream Signalized Intersection

1) In the case of offset control

It is assumed that the offset is controlled for vehicles which run straightaway between two adjacent signalized intersections. The variables and subscripts used following equations are listed in TABLE I. Although the variables vary depending on the location and time, their subscripts i, j, m and k are omitted for simple descriptions in the right side of following equations. The mean link travel time is analyzed for moving directions at the downstream signalized intersection as follows:

a) In the case of straightaway

- running time

The running time is analyzed using the link distance d, the queue length y_s and the running speed v

$$T_r(i,j,m,k) = t_{run} \tag{6}$$

with

$$t_{run}(i,j,m,k) = (d - y_s)/v \tag{7}$$

- stopping time

The stopping time is analyzed using the yellow time, red time and the starting delay of the vehicle

$$T_s(i,j,m,k) = P_s\{P_y(t_y/2 + t_r + t_s) + P_r(t_r/2 + t_s)\} \tag{8}$$

In the case of short distance between two adjacent signalized intersections, vehicles almost stop from the biginning of the red time

$$T_s(i,j,m,k) = P_s\{P_y(t_y/2 + t_r + t_s) + P_r(t_r + t_s)\} \tag{9}$$

b) In the case of right-turn

- running time

The running time consists of the straightaway running time and the outgoing time of the right-turn lane queue

$$T_r(i,j,m,k) = t_{run} + t_{cr} \tag{10}$$

with

$$t_{cr}(i,j,m,k) = y_r / 2\varphi_r \tag{11}$$

- stopping time

The stopping time consists of the time difference of the green initiation between straightaway and right-turn direction and the starting delay of the vehicle

$$T_s(i,j,m,k) = t_{dr}/2 + t_s \tag{12}$$

c) In the case of left-turn

- running time

The running time is analyzed in the same way as the right-turn

$$T_r(i,j,m,k) = t_{run} + t_{cl} \tag{13}$$

$$t_{cl}(i,j,m,k) = y_l / 2\varphi_l \tag{14}$$

- stopping time

The stopping time is also analyzed in the same way as the right-turn

$$T_s(i,j,m,k) = t_{dl}/2 + t_s \tag{15}$$

2) In the case of non-offset control

The vehicles encounter any traffic signals at downstream signalized intersection.

a) In the case of straightaway

- running time

The running time is analyzed by the summation of expected value for each traffic signal

$$T_r(i,j,m,k) = P_g \cdot t_{run} + P_y(t_{run} + t_{cs}) + P_r(t_{run} + t_{cs}) \tag{16}$$

with

$$t_{cs}(i,j,m,k) = y_s / 2\varphi_s \tag{17}$$

- stopping time

The stopping time is analyzed by the summation of expected values for the yellow and red traffic signals and the starting delay of the vehicle

$$T_s(i,j,m,k) = P_y(t_y/2 + t_r + t_s) + P_r(t_r/2 + t_s) \tag{18}$$

b) In the case of right-turn

- running time

The running time is analyzed by taking into account the probability of non-passing through the right-turn lane at the downstream signalized intersection during the green time

$$T_r(i,j,m,k) = P_g(t_{run} + \alpha_r \cdot t_{cr}) + P_y(t_{run} + t_{cr}) + P_r(t_{run} + t_{cr}) \tag{19}$$

- stopping time

The stopping time is also analyzed by taking into account the same probability of non-passing through the right-turn lane as the running time

$$T_s(i,j,m,k) = P_g\{\alpha_r(t_g/2 + t_y + t_r + t_{dr} + t_s)\} + P_y(t_y/2 + t_r + t_{dr} + t_s) + P_r(t_r/2 + t_{dr} + t_s) \tag{20}$$

c) In the case of left-turn

The running and stopping time are analyzed in the same way as the right-turn

- running time

$$T_r(i,j,m,k) = P_g(t_{run} + \alpha_l \cdot t_{cl}) + P_y(t_{run} + t_{cl}) + P_r(t_{run} + t_{cl}) \tag{21}$$

- stopping time

$$T_s(i,j,m,k) = P_g\{\alpha_l(t_g/2 + t_y + t_r + t_{dl} + t_s)\} + P_y(t_y/2 + t_r + t_{dl} + t_s) + P_r(t_r/2 + t_{dl} + t_s) \quad (22)$$

B. In the Case of Congestion at the Downstream Signalized Intersection.

It is assumed that the traffic signals are controlled optimally and the vehicles run through at the downstream signalized intersection by waiting for only one green time.

1) In the case of straightaway

• running time

The running time consists of the running time and outgoing time of straightaway lane queue for each traffic signal

$$T_r(i,j,m,k) = P_g(t_{run} + t_{cs}) + P_y(t_{run} + t_{cs}) + P_r(t_{run} + t_{cs}) \quad (23)$$

that is

$$T_r(i,j,m,k) = t_{run} + t_{cs} \quad (24)$$

• stopping time

The stopping time is analyzed by the summation of expected values for each traffic signal and the starting delay of the vehicle

$$T_s(i,j,m,k) = P_g(t_g/2 + t_y + t_r + t_s) + P_y(t_y/2 + t_r + t_s) + P_r(t_r/2 + t_s) \quad (25)$$

2) In the case of right-turn

• running time

The running time is analyzed by the summation of expected values for the straightaway running time and the outgoing time of right-turn lane queue

$$T_r(i,j,m,k) = P_g(t_{run} + t_{cr}) + P_y(t_{run} + t_{cr}) + P_r(t_{run} + t_{cr}) \quad (26)$$

that is

$$T_r(i,j,m,k) = t_{run} + t_{cr} \quad (27)$$

• stopping time

The stopping time is analyzed by the summation of expected values for traffic signals, time difference of green initiation between straightaway and right-turn directions and the starting delay

$$T_s(i,j,m,k) = P_g(t_g/2 + t_y + t_r + t_{dr} + t_s) + P_y(t_y/2 + t_r + t_{dr} + t_s) + P_r(t_r/2 + t_{dr} + t_s) \quad (28)$$

3) In the case of left-turn

The running and stopping time are analyzed in the same way as the right-turn

• running time

$$T_r(i,j,m,k) = t_{run} + t_{cl} \quad (29)$$

• stopping time

$$T_s(i,j,m,k) = P_g(t_g/2 + t_y + t_r + t_{dl} + t_s) + P_y(t_y/2 + t_r + t_{dl} + t_s) + P_r(t_r/2 + t_{dl} + t_s) \quad (30)$$

C. OD Travel Time

The mean OD travel time is calculated by summing up the running and stopping time of each link along its route

$$T_{OD}(k) = \sum_i \sum_j \sum_m \{T_r(i,j,m,k) + T_s(i,j,m,k)\} \quad (31)$$

IV. MEASUREMENT OF LINK TRAVEL TIME

The link travel time are measured by the average rate of speed of the traffic stream which is more accurate and general than the floating car technique and other measurement methods. The driver selects a speed that is the average rate of speed of the traffic stream without trying to balance the passing [5]. One observer starts the stop watch at the beginning of the test run, and the other records the elapsed time at various check points along the route. The time, the location and the cause of stop are recorded. In this paper, the link travel time are measured for an urban road network in Fukuyama city shown in Fig.3., Japan. The time interval and the number of runs are shown in TABLE II.

V. ESTIMATION OF LINK TRAVEL TIME

The mean link and OD travel time are estimated about two routes in Fukuyama city shown in Fig.4 and Fig.5 according to their analyses. The time interval is selected for the traffic network before and during rush hours as shown in TABLE II. The necessary traffic information such as the signal control parameters, queue lengths, saturation flows and starting delays are arranged for the estimation of the travel time by using the simulation results of the signal control system and the measurement data. For example, the Route No.1 starts from the (1,1) signalized intersection and turns to the left at the (2,1) signalized intersection then goes along the Route 2 and turns to the right at the (2,3) signalized intersection, then turns to the left at the (3,3) signalized intersection and arrives at the (3,4) signalized intersection. This route includes one right-turn and two left-turns along its route. The estimation values of the mean link travel time are compared with the measurement values of the test-car technique for each time interval. The estimation errors of both the stopping time and the travel time become large at the (2,1) signalized intersection in TABLE III and TABLE IV. The mean link travel time are accumulated along the Route No.1 and the Route No.2 during the rush hour in TABLE III and TABLE IV. As the results, the mean OD travel time of the Route No.1 is estimated in a relatively good accuracy as shown in TABLE III.

VI. CONCLUSIONS

The mean link travel time are analyzed taking the traffic flow dynamics, signal control parameters and moving direction of vehicles at downstream signalized intersections into account in urban road networks. The estimation values of the mean link travel time are compared with the measurement values of the test-car technique for two routes in Fukuyama city, Japan. The following have been shown.

1) The mean link travel time are analyzed taking the traffic flow dynamics, signal control parameters and moving direction of vehicles at downstream signalized intersections into account.
2) The link travel time are measured about two routes in Fukuyama city, Japan by the test-car technique.
3) It is confirmed that the mean link travel time are estimated in relatively good precision without the links of right- and left-turns by comparing between the estimation values and the measurement values.

It is planned in future that the number of runs by the test-car technique is increased so as to improve the accuracy of both estimation values and measurement values.

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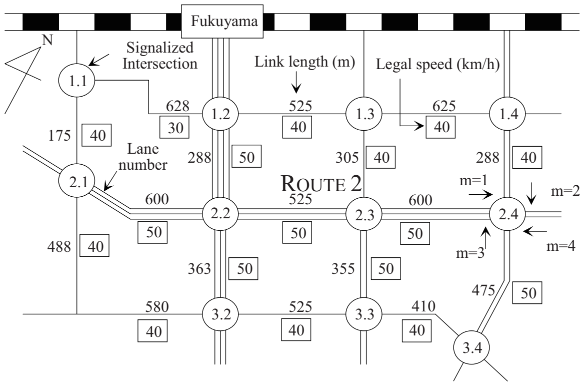

Figure.3 Traffic network in Fukuyama city.

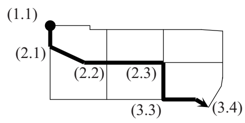

Figure.4 Route No.1.

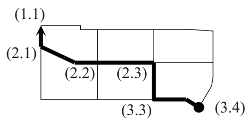

Figure.5 Route No.2.

TABLE II. CLASSIFICATION OF TIME INTERVAL.

Classification	Time interval	Number of runs
Before rush hour	16:00 ~ 17:00	10
During rush hour	17:00 ~ 18:00	10

TABLE III. THE ESTIMATION ERRORS OF MEAN LINK TRAVEL TIME FOR THE ROUTE NO.1 DURING RUSH HOUR.

		(1.1)	(2.1)	(2.2)	(2.3)	(3.3)	(3.4)
Running Time	Estimation Value(s)	0.0	37.2	103.4	170.9	217.1	267.7
	Measurement Value(s)	0.0	37.2	103.2	164.2	203.8	253.3
	Relative Error(%)	0.0	0.0	0.2	4.1	6.5	5.7
Stopping Time	Estimation Value(s)	0.0	50.6	72.2	222.7	243.0	281.2
	Measurement Value(s)	0.0	126.4	164.5	266.2	277.5	311.8
	Relative Error(%)	0.0	-60.0	-56.1	-16.3	-12.4	-9.8
Travel Time	Estimation Value(s)	0.0	87.8	175.6	393.6	460.1	548.9
	Measurement Value(s)	0.0	163.6	267.7	430.4	483.3	565.1
	Relative Error(%)	0.0	-46.3	-34.4	-8.6	-4.8	-2.9

TABLE IV. THE ESTIMATION ERRORS OF MEAN LINK TRAVEL TIME FOR THE ROUTE NO.2 DURING RUSH HOUR.

		(3.4)	(3.3)	(2.3)	(2.2)	(2.1)	(1.1)
Running Time	Estimation Value(s)	0.0	59.8	120.4	187.0	287.9	313.2
	Measurement Value(s)	0.0	56.0	113.5	178.7	278.0	303.5
	Relative Error(%)	0.0	6.8	6.1	4.6	3.6	3.2
Stopping Time	Estimation Value(s)	0.0	40.8	92.3	135.5	302.0	330.9
	Measurement Value(s)	0.0	42.0	91.6	129.2	223.6	227.5
	Relative Error(%)	0.0	-2.9	0.8	4.9	35.1	45.5
Travel Time	Estimation Value(s)	0.0	100.6	212.6	322.5	589.8	644.0
	Measurement Value(s)	0.0	98.0	205.1	307.9	501.6	531.0
	Relative Error(%)	0.0	2.7	3.7	4.7	17.6	21.3