PRACTICAL TRAFFIC ASSIGNMENT FOR MULTIPLE HIGHWAY ROUTES USING DISTRIBUTION OF VALUES OF TIME

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INTRODUCTION

To forecast traffic volume of future highway network, the Hanshin Expressway Public Corporation has been using the Incremental Assignment (IA) method based on the shortest path in conjunction with the highway share curve for about 30 years with some updates of the parameters. This method is easy to apply and shows satisfactory goodness-of-fit to the observed flows for relatively simple urban highway networks with flat toll policy, but the following problems have been pointed out. The value of time (VOT) used in the share curve is point-estimated from the average wage rate and, therefore, is sometimes far from the perceived VOT relevant to the actual route choice behavior. Furthermore, multiple routes are loaded only due to flow dependent link travel time and, therefore, the method cannot produce practical assignment for dense urban highway networks where competing multiple highway routes exist.

The research presented in this paper, first, estimates the distribution of VOT of drivers from revealed and stated preferences in the highway vs. city street choice situations and then assigns traffic according to the estimated distribution of VOT. This method can assign traffic to competing multiple highway routes and, hence, yield more realistic impact analysis of toll policies.

1. ESTIMATION OF DISTRIBUTION OF VOT

1.1. Framework for Estimating VOT

The Hanshin Expressway Public Corporation has been using a traditional highway share function with a single VOT estimated by the average income approach, namely, dividing the National Income by the total work hours. The VOT estimated in this way is used to calculate the travel time equivalent to the highway toll for the highway share function as follows:

$$P = \frac{1}{1+\alpha R^{\gamma}} - \beta \tag{1}$$

where

$$R = \frac{T_t + \frac{C}{\lambda} + \delta}{T_c - T_a + \delta} \tag{2}$$

P = highway share;
R = ratio of highway and city street travel times;
T_c = travel time by city street;
T_l = linehaul travel time by highway;
T_a = access and egress travel time by highway;
C = highway toll;
λ = VOT; and
$\alpha, \beta, \gamma, \delta$ = unknown parameters.

However, the VOT estimated by the average income approach is often far from the driver's perceived VOT which actually determines the route. Furthermore, the actual VOT are considered to be widely distributed in the population rather than a single value. This heterogeneity of VOT partly explains the observed flows that multiple routes are loaded for a particular O-D pair. Assignment methods with a single VOT load multiple routes only when travel time of the shortest route reaches that of the second shortest due to congestion. Consequently, the assignment results by traditional method often show serious disagreement with the observed flows for dense urban highway networks where number of competing routes exist.

This research conducted an interview survey to drivers to estimate the distribution of drivers' VOT. Preference information on actual or hypothetical choices between a highway with toll and a city street enables one to identify generalized cost functions, or utility functions, of both routes. The ratio of weights, or coefficients, of travel time and monetary cost gives an estimate of VOT as follows:

$$\lambda_n = \frac{\beta_{tn}}{\beta_{cn}} \tag{3}$$

where

$$V_{hn} = \beta_{tn} T_{hn} + \beta_{cn} C_{hn} \tag{4}$$

$$V_{cn} = \beta_{tn} T_{cn} + \beta_{cn} C_{cn} \tag{5}$$

(Subscripts, h and c, denote highway and city street routes, respectively. Subscript, n, denotes individual n.)
V = utility;
T = travel time;
C = travel cost including toll;
β_t = coefficient for travel time;
β_c = coefficient for travel cost; and
λ = value of time.

VOT estimated as above requires identification of utility functions, more specifically, estimation of coefficients, β's. With standard disaggregate choice data the coefficients can be estimated for the population or a market segment. This type of estimation assumes that coefficients have common values for the population or a market segment and, therefore, that so do VOT.

If large enough number of repeated choices for each individual are observable, the coefficients can be estimated for each individual and, therefore, so can VOT. Repeated choices are often observable by stated preference surveys that presents several hypothetical choice scenarios to the respondents and asks their preferences.

Another approach to estimate individual-specific VOT is the direct estimation from transfer price data. Transfer price data are obtained by presenting to the respondents a city street route and a competing highway route and asking them about the toll that makes two routes indifferent. Since utility values of the two indifferent routes are considered to be the same, VOT is calculated as follows:

$$\lambda_n = \frac{\beta_{tn}}{\beta_{cn}} = \frac{C_{hn}-C_{cn}}{T_{cn}-T_{hn}} \tag{6}$$

1.2. Estimation Results of VOT

An interview survey to randomly selected 400 licence holders was conducted in Osaka, Japan to obtain 375 valid samples. To elicit revealed preferences (RP) the interviewers first asked about the highway routes that the respondents usually use. Then, stated preference (SP) questions were asked. Some of them directly asked for the willingness-to-pay for hypothetical highway routes to get transfer price data and others elicit preferences to hypothetical multiple routes for several origin-destination pairs.

Firstly, the RP data of the usual highway route and the alternative city street route are used to estimate the individual lower bound of VOT. The alternative city street route for an individual was identified by the analysts. Since the respondent prefers the highway route to the city street route, the lower bound of VOT is estimated in the following way:

$$V_{hn} = \beta_{tn}T_{hn} + \beta_{cn}C_{hn} \geq \beta_{tn}T_{cn} + \beta_{cn}C_{cn} = V_{cn} \tag{7}$$

then

$$\lambda_n^l = \frac{\beta_{tn}}{\beta_{cn}} \geq \frac{C_{hn}-C_{cn}}{T_{cn}-T_{hn}} \tag{8}$$

where

λ_n^l = lower bound of VOT for individual n.

The distribution of the lower bounds of VOT is presented in Fig. 1. The mean is 22.6 yen/min. and the standard deviation is 16.2 yen/min.

Next, willingness-to-pay for the usual highway route is used to estimate the individual VOT using eq. (6). The distribution of VOT is shown in Fig. 2. The mean is 24.3 yen/min. and the standard deviation is 19.9 yen/min.

Then, each respondent is shown six different existing highway routes and is asked to respond willingness-to-pay for each route. Thus, six VOT is obtained from each respondent and the mean is calculated from six VOT for each respondent. Fig. 3 shows the distribution of these mean values of VOT. The mean of the distribution is 22.0 yen/min. and the standard deviation is 6.38 yen/min.

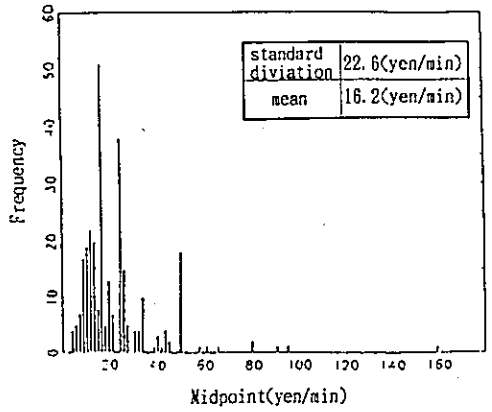

Fig. 1. The distribution of lower bounds of VOT

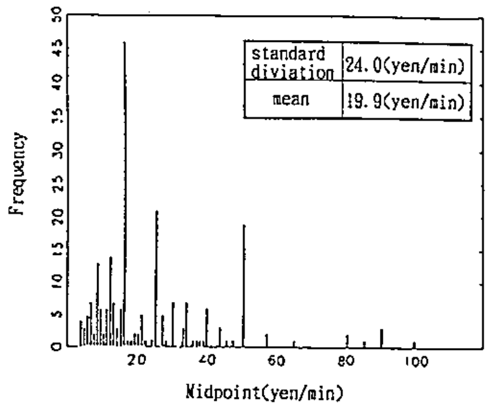

Fig. 2. The distribution of VOT (willingness-to-pay for the usual highway route)

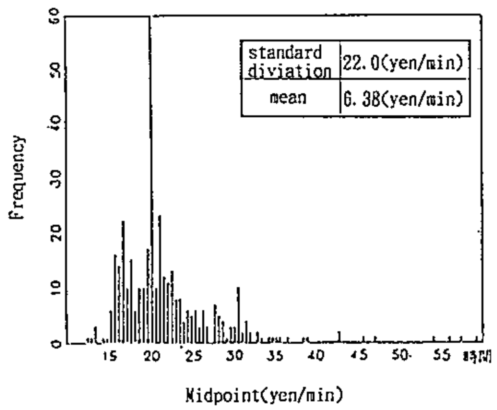

Fig. 3. The distribution of VOT (willingness-to-pay for the six different existing highway routes)

Supplemental SP data are also obtained in the form of "stated choice probabilities". More specifically, a city street route with specified travel time and alternative eight highway routes are presented to the respondent, who has to respond the presumed choice probability of each of the eight highway routes against the city street route for three different trip purposes, i.e., business, commuting, and leisure. Since stated choice probabilities are obtained, one can estimate the utility functions (eqs. (4) and (5)) using the binary logit model. Alternatively, since the preference order for the eight highway routes are observable, the ordered probit model is applicable to estimate the utility functions.

Approximately the same VOT, around 13.5 yen/min., are obtained for the three trip purposes and by the two types of models. This may imply that one can use the same VOT distribution for different purposes in this particular context.

Lastly, the obtained VOT distribution of Fig. 2 is found to be fitted to the log-normal distribution with high degree of confidence by the goodness-of-fit test.

Consequently, this VOT analysis has revealed that different types of questions, even revealed and stated preference questions, yield approximately the same VOT distribution, which is log-normally distributed with mean 24 yen/min., or 10 US$/hour. This mean value is significantly lower than the VOT estimated by the average wage rate approach, which is 40 yen/min., or 17 US$/hour.

2. HIGHWAY MULTIPATH ASSIGNMENT

2.1. Framework of Multiple Highway Path Assignment

In this study, another important purpose is to develop a practical assignment to the Highway Multipath (HM). The term "Highway Multipath (HM)" is defined in this study as the multiple paths that are chosen from highway network and available to travelers of a certain O-D pair. And the paths are competitive one another.

In most previous studies, the Incremental Assignment (IA) is used and the shares of traffic volume between highways and city streets are explained using the diversion equation. In each step of these methods, two paths are chosen, one path being chosen from the city street network and another path from all the networks (composed of the city streets and the highway network), for each O-D pair. Each path is the shortest for each network. Traffic volume divided through the diversion equation is assigned to these two paths. This assignment method repeats this step so that traffic volume is assigned to multiple paths. In this study, we call this method the Diversion Curve (DC) method. But in this method, if the total capacity of network exceeds the traffic demand, traffic volume is assigned to only one path which is the shortest of the two paths mentioned above. Accordingly, the question whether these methods are able to actually predict traffic volume on network in urban area now arises.

In this study, we develop the method of assignment to the highway multipaths by using the Minimum Sacrifice Route Searching (MSR) method and Highway Multipath Choice (HMC) method as the principle of the search for the highway paths. We assign the actual traffic volume to the network in order to test the ability of traffic volume prediction using the MSR method, the HMC method and the DC method. From the results of these tests, we analyze the practicability of each method. The viewpoints of this comparative analysis are as follows:

1) the ability of traffic volume prediction on the highway multipaths;
2) the ability of description of actual route choices; and
3) the practicability (especially about CPU time).

It is important to keep in mind that the Incremental Assignment method is used for all the assignment cases in this study.

3.2. Highway Multipath Assignment Method

3.2.1. MSR method

In the MSR method, considering the distribution of VOT, the Corrected Travel Time (CTT) on each highway link is calculated by the following formula:

$$T = t + \frac{F}{\lambda} \qquad (9)$$

where

T = Corrected Travel Time (CTT),
F = highway toll,
λ = VOT,
t is the actual travel time.

In the MSR method the path with the minimal CTT is selected. The assignment is carried out in the following steps:

Step 1 Calculating the velocity and the travel time on each link at the current iteration. The link velocities are calculated by using the Q-V curve and the travel time on each link is calculated based on these velocities. "Q" represents the traffic volume on each link and "V" does the link velocity. Table 1 indicates the five bins of VOT with each representative values. For the highway routes, the toll is converted into five travel time equivalents using these five VOT and, therefore, five CTT are calculated.

Step 2 Searching for the shortest path corresponding to each VOT group. Five paths are chosen according to the minimal CTT.

Step 3 Assigning traffic volume to each path. OD flow is assigned to five paths mentioned above according to the assignment factor indicated in Table 1.

Table 1. The Rank of VOT and assignments factor

Rank	VOT(yen/min/veh)	assignment factor
$\lambda 1$	7.8	0.1021
$\lambda 2$	14.3	0.2346
$\lambda 3$	24.7	0.3277
$\lambda 4$	44.2	0.2624
$\lambda 5$	78	0.0732

3.2.2. The HMC method

In the HMC method, it is necessary to divide the highway network into three subsets of paths. We assume that the highway network consists of subset of the O-ON paths (the paths from the origin to the "on" ramp of the highway) , ON-OFF paths (the paths from the "on" to "off" ramps) and OFF-D paths (paths from the "off" ramp to the destination). We combine the paths selected from each subset in order to make the multiple O-ON-OFF-D paths in the highway network. And the traffic volumes are assigned to these paths. The process of the Incremental Assignment including the HMC method is as follows:

Step 1 Calculating the velocity and the travel time on each link at the current iteration. The link velocities are calculated through using the Q-V curve and the travel time on each link is calculated based on these velocities.

Step 2 Searching for the paths both in the city street and highway networks and making the multiple paths from the origin to destination that are used for assignment. Firstly, four kinds of networks are created as follows:
1. ON-OFF network (highway network)
2. O-ON and OFF-D networks (city street network and ramp links)
3. whole network (highway and city street networks, ramp links)
4. city street network.

Then the multiple O-ON-OFF-D paths used for traffic volume assignment are chosen according to the process given below:
1. making the arrangement of the ON-OFF paths
2. making the arrangement of the O-ON and OFF-D paths
3. converting the arrangement of the ON-OFF, O-ON and OFF-D paths into the arrangement of the O-ON-OFF-D paths
4. searching for the shortest path in the whole network
5. searching for the shortest path in the city street network
6. choosing the O-ON-OFF-D paths according to the criteria given below
    1) condition of constraints of travel time:
        $(T_{ijr} - T_{ij1}) < 30$ min. and $(T_{ijr} / T_{ij1}) < 1.5$
    2) condition of constraint of travel time in the city street network:
        $T_{ijr} \leq T_{ij0}$
    3) choosing the shortest path among the paths including the loop road's link
    where
        T_{ij0} = the travel time of the shortest path in city street network;
        T_{ij1} = the travel time of the shortest path in the whole network; and
        T_{ijr} = the travel time of the multiple highway paths.

Step 3 Calculating the assignment factors and assigning traffic volume. Firstly, the assignment factors of the highway routes are calculated through using the diversion equation. The diversion equation includes T_{ij0} and T_{ij1} as the explanatory variables. The diversion equation is as follows:

$$P_{ij} = \frac{1}{1+\alpha T^{\gamma}} - \beta \tag{10}$$

Then the assignment factors of each highway path are calculated based on the probabilistic multipath traffic assignment principle using T_{ij1} and T_{ijr}. The parameter n cannot be obtained at present. Therefore, considering the results of the previous studies, the value of n assumed to be set at 6.0 in order to illustrate the effect of travel time ratio.

$$P_{ijr} = \frac{T_{ijr}^{-n}}{\sum_{r} T_{ijr}^{-n}} \tag{11}$$

where T is the travel time ratio.
The OD flow on each highway path is calculated by multiplying the total OD flow by these assignment factors of highway paths. And we assign the traffic volumes to the network.

3.2.3. The illustrations of the search for the paths

In this study, in order to compare the abilities of the methods to search for the paths, the traffic volume assignment to the network are conducted by the three methods mentioned above, the Diversion Equation (DE) method, the MSR method, and the HMC method. The Incremental Assignment (IA) technique is universally applied for all the methods.

In the DE method, a path consisting of the city street links and a path including highway links are selected for one O-D pair. The travel time of each path selected is the shortest. The highway toll is not included as the explanatory variable of the search for the shortest paths. The toll is used for calculating the assignment factors based on the diversion equation. The illustration of selecting paths is indicated in Fig. 4.

In the MSR method, for one O-D pair, the highway multipaths are selected based on the value of Corrected Travel Time (CTT) mentioned above. But on the other hand, the city street path selected is only one for each O-D pair. Since the CTT is calculated through adding the highway toll converted by each time value to the actual travel time of the path, the toll is included as the explanatory variable of the path search. The illustration of selecting paths is indicated in Fig. 5.

In the HMC method, when the highway multipaths, namely the O-ON-OFF-D paths, are selected, the highway toll is not included as the explanatory variable of the search for these paths. The toll is used for calculating the assignment factors. Fig. 6 indicates the illustration of the search for paths.

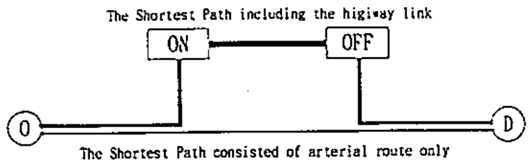

Fig. 4. The Illustration of Selecting Paths in DEM Method

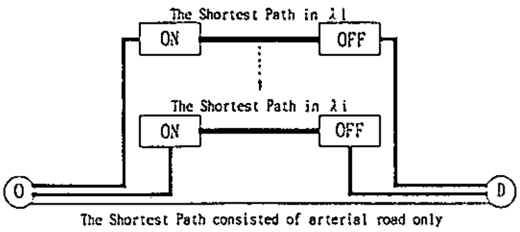

Fig. 5. The Illustration of Selecting of Paths in MSR Method

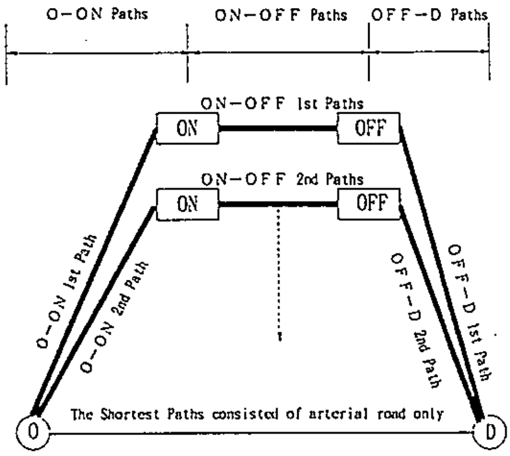

Fig. 6. The Illustration of Selecting Paths in HMC Method

3.3. The Traffic Volume Assignment

3.3.1. The premises of the assignment

In assigning the traffic volumes, the following premises are assumed:

1. The network consists of the Hanshin Highway, the national roads and the city streets managed by the prefectures in 1989.
2. Considering the level of roads included the network, the zones divided corresponds to the municipalities. The number of zones is 147.
3. The surveys in order to acquire the basic data of OD trips are as follows:
   1) the traffic survey in the whole land conducted by Ministry of Construction in 1985 (used to make the OD table)
   2) the 18th Hanshin Highway OD survey (the observed values of traffic volumes on the highway).
4. The number of iteration in the IA method is set at four.

5. The diversion equation used in the DE method and HMC method is given below.

$$P = \frac{1}{1+\alpha T^{\gamma}} - \beta \tag{12}$$

$$T = \frac{S_1+d+R/C}{S_0-S_2+d} \tag{13}$$

where
P =assignment factor
T = travel time ratio
S_0 = travel time when the traveler use the city street path
S_1 = travel time on the section of highway of the highway path users
S_2 = travel time on the section of city streets of the highway path users
R = highway toll
C = time value (c=51.0 yen/min/veh.)
α, β, γ, d : constants (α=3.0, β=0.03, γ=3.0, d=0)

6. The assignment factors needed in the MSR method are indicated in Table 1.

In this study, three kinds of traffic volume assignments are conducted according to the premises mentioned above. The cases of assignments are given below:
Case 1: IA by using the diversion equation (DE method)
Case 2: IA including the MSR method as the means of path search
Case 3: IA including the HMC method as the means of path search

3.3.2. The comparative analysis of the assignment methods

(1) Test of the assignment methods for the ability of traffic volume reproduction

The term "traffic volume reproduction" is defined in this study as predicting the past or current traffic volume by using each assignment method and the former data of OD trips and network available at present. Table 2 indicates the traffic volumes, the average trip length (ATL) on Hanshin Highway and the average length of O-D trips (ALO) to use this highway in every assignment case. In this table, values measured actually are obtained through the 18th Hanshin Highway OD survey. From a macroscopic point of view, namely comparing the traffic volumes and the average trip length, it can be said that every assignment method can almost reproduce the traffic volumes on the Hanshin Highway.

(2) Comparison of the paths used in each assignment method

Table 3 indicates the number of paths used for the typical OD pairs in each assignment case. First, we compare the number of paths selected in each assignment case. It is obvious that the number of paths in the MSR method and the HMC method is greater than that in the DE method. Especially, the HMC method selects many paths. Because the HMC method is apt to select the paths that include the same highway line and the different on or off ramp for the same O-D pair.

Next, we compare the Hanshin Highway paths actually used in the 18th OD survey with the paths selected in each assignment method. Though there is no space for indicating the illustrations, we can find that the number of paths selected in Cases 2 and 3 is greater than that in Case 1. And we see that the paths selected in Cases 2 and 3 are similar to those actually used.

Table 2. The traffic volumes of Hanshin Highway in each Method

	Values measured actually	DE Method	MSR Method	HMS Method
Traffic Volumes	726,000	742,000	711,000	755,000
ATL(km)	15.4	15.1	16.8	15.7
ALO(km)	44	40	39	42.7

Table 3. Number of Paths used on Highway for typical O-D pair

Typical O-D pair	Actually	DE Method	MSR Method	HMS Method
Chuo-ku ~Takatsuki city	8	7	10	86
Chuo-ku ~Fujiidera city	8	2	6	56
Chuo-ku ~Sakai city	8	2	4	44
Chuo-ku ~Kyoto city	8	6	12	36
Sakai city ~Toyonaka city	8	4	5	33
Sakai city ~Moriguchi city	6	2	3	14

Table 4. The specification of the computer

CPU	IBM 3090-200J
O/S	MVS/ESA V3.1.1
Calculation ability	42mips
Program language	Fortrun

Table 5. CPU Time in each Method

	DE Method	MSR Method	HMS Method
read data (sec.)	0.2643	0.3089	0.3395
calculating link travel time (sec.)	0.0063	0.0135	0.0085
path search and assignment (sec.)	39.3894	82.4467	125.6912
All CPU Time (sec.)	39.66	82.7691	126.0392

Table 6. Computational Space needed in each Method

	DE Method	MSR Method	HMS Method
Number of the arrangement of Paths (Number)	85,000	269,000	177,000
Space of the arrangement of Paths (MB)	39	125	82
Program space (MB)	3.5	3.5	6

(3) Comparison of CPU time

The specifications of the computer are given in Table 4. Table 5 indicates the CPU time in each assignment method. The CPU time in the MSR method is 2.1 times and that in HMC method is 3.2 times as large as that in the DE method. As the assignment factors are apriori decided in the MSR method, the CPU time needed to calculate the assignment factors is half as much as that in DE method. The CPU time needed calculate the assignment factors in the HMC method is 13.0 times as large as that in the DE method, because in HMC method there exist many paths and both diversion rate and assignment factor must be calculated.

Table 6 indicates the the computational space in the computer memory. The space needed for the program in the MSR method is almost as large as that in the DE method. The program space in the HMC method is 1.7 times as large as that in DE method. The space needed for the arrangement of paths in the MSR method is 3.2 times and that in the HMC method is 2.1 times as large as that in the DE method.

3. CONCLUSION

The study presented in this paper includes two research topics: 1) estimation of drivers' VOT distribution from RP and SP questions, and 2) application of the MSR and HMC methods to highway multipath assignment using the VOT distribution. From the study of VOT, reasonable VOT distributions were obtained from both RP and SP analyses. The MSR and HMC methods have yielded more realistic assignment that loads traffic on highway multipaths compared with the traditional DE method.

Further investigation would be required on the following points:

1) Professional drivers' VOT may be significantly different from the VOT estimated in this study. Also, the estimated VOT is fully valid only under the current network condition, which implies uncertainty in VOT under the different future highway network.
2) In order to apply the MSR or HMC methods to the area with large number of zones new algorithm should be developed to reduce CPU time and memory space.
3) Sensitivity analysis on the split of the VOT distribution is needed for the MSR method.

Lastly, the authors would like to thank Prof. Sasaki of Kyoto Univ. and Prof. Inoue of Fukuyama Univ. for their insightful advices.