THE COMBINED MODAL SPLIT/ASSIGNMENT MODEL IN THE TOKYO METROPOLITAN AREA

Takuya MARUYAMA
Graduate Student
Graduate School of Frontier Sciences
University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo,
113-8656, Japan
Fax: +81-3-5841-8527
E-mail: maruyama@ut.t.u-tokyo.ac.jp

Yasunori MUROMACHI
Associate Professor
Engineering Research Institute
School of Engineering, the Univ. of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo,
113-8656, Japan
Fax: +81-3-5841-8527
E-mail: ymuro@ut.t.u-tokyo.ac.jp

Noboru HARATA
Professor
Graduate School of Frontier Sciences
University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo,
113-8656, Japan
Fax: +81-3-5841-8527
E-mail: nhara@ut.t.u-tokyo.ac.jp

Katsutoshi OHTA
Professor
Graduate School of Engineering
University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo,
113-8656, Japan
Fax: +81-3-5841-8527
E-mail: katsuohta@ut.t.u-tokyo.ac.jp

Abstract: In this study, we build a combined modal split/assignment model in the Tokyo Metropolitan Area (TMA), and make a simple policy evaluation. At first, an equivalent mathematical problem is shown. A road and railway network in TMA by GIS data is constructed and we check the reproduction accuracy of the model. Next, we estimate the parameters in modal split model. Finally, the combined model is calculated and congestion charging policy is evaluated. The policy effect estimated by this model is higher than that by fixed demand model because this model can consider not only the users' route change but also the modal-shift.

Key Words: combined modal split/assignment model, congestion charging policy, GIS

1. INTRODUCTION

The Four Step Model has been widely used in Metropolitan Transportation Planning, but it has an inherent weakness. For example, its predictions may not be internally consistent.

These deficiencies have motivated some attempts to predict the four steps simultaneously. The first of such models appeared in the elastic demand traffic assignment problem model of Beckmann *et al.* (1956). Evans (1976) extended the formulation to include trip distribution, assuming fixed trip generation and an entropy model for trip distribution. Florian and Nguyen (1978) extended the formulation to include modal split. Safwat and Magnanti (1988) combined all four steps.

However, these combined models were rarely applied to a real-world transportation system. Safwat (1987) applied the simultaneous equilibrium model to the intercity passenger travel in Egypt. Kawakami and Shi (1995) applied a combined modal split and assignment model to Nagoya City. Abrahamsson and Lundqvist (1999) applied combined trip distribution, modal split, and assignment model to the Stockholm region. Hasan and Safwat (2000) compared the simultaneous approach and the conventional sequential approach in Tyler, Texas.

The objective of this paper is to develop the combined modal split/assignment model in the Tokyo Metropolitan Area that can evaluate relevant transport policy.

Tokyo has been suffering from chronic traffic congestion, and environmental degradation such as air pollutions. Now Tokyo Metropolitan Government plans to alleviate the traffic congestion by developing policies to enhance traffic flow. They promote urban transport policies that emphasize transportation demand management (TDM). One such policy is the introduction of a road pricing (congestion charging) into the downtown area. Therefore, reliable models which can forecast the effect of a congestion charging policy is highly needed now.

In behavioral terms, road users can make six different responses, when faced with congestion pricing on a network. They can change the route, destination, the time of their departure, mode, vehicle-occupancy, and the frequency of their trip-making or opt out entirely. Any model should be able to reflect these behavioral responses (Hills, 1993).

The combined transport network models can deal with most of these responses properly. Our model, the combined modal split/assignment model, can forecast the users' route change and modal sift in a congestion charging policy. Our simultaneous equilibrium model produces the consistent travel cost between the output of assignment model and the input of mode choice model.

2. MODEL FORMULATION

We assume the number of trips between each origin r and destination s, $\bar{q}_{rs}$, is fixed. There are only two modes; automobile and transit (railway).

The transit travel cost between each origin r and destination s, c_{rs}^{tran} is constant, expressed in travel time units. The flow-independent cost function in railways may be unreasonable assumption, because in TMA the railways are very crowded in the morning or evening rush hours. However, we accept this assumption for the simplicity.

The automobile travel cost between r and s, c_{rs}, depends on traffic flow, which increases as the flow grows on automobile networks. These cost include not only travel time but also fare and other resistance which converted into travel time units.

The mode choice between each O-D pair is based on following logit model. The automobile flow between origin r and destination s is given by

$$q_{rs} = \bar{q}_{rs} \frac{1}{1 + \exp(-\theta(c_{rs}^{tran} - c_{rs}) + \Psi_{rs})} \tag{1}$$

where θ and Ψ_{rs} are parameters, and the transit flow is given by $q_{rs}^{tran} = \bar{q}_{rs} - q_{rs}$. Note that this logit mode choice model includes a constant, Ψ_{rs}, which captures the effects of all factors other than the (generalized) travel-time difference on the mode choice.

If the state in automobile networks is described by Wardrop's First Principle, the modal split/assignment model is formulated as following equivalent mathematical problem (Sheffi, 1985).

$$\min . Z(\mathbf{x}, \mathbf{q}, \mathbf{q}^{tran}) = \sum_{a \in A} \int_0^{x_a} t_a(\omega)\, d\omega + \sum_{r \in R} \sum_{s \in S} \int_0^{q_{rs}^{tran}} \left\{ \frac{1}{\theta} \ln\left(\frac{\omega}{\bar{q}_{rs} - \omega} \right) + c_{rs}^{tran} - \frac{1}{\theta} \Psi_{rs} \right\} d\omega \tag{2a}$$

$$\text{s. t.} \quad \sum_{k \in K_{rs}} f_k^{rs} + q_{rs}^{tran} = \bar{q}_{rs}, \forall r \in R, s \in S \tag{2b}$$

$$f_k^{rs} \geq 0, \forall k \in K_{rs}, r \in R, s \in S \tag{2c}$$

$$x_a = \sum_{r \in R} \sum_{s \in S} \sum_{k \in K_{rs}} \delta_{a,k}^{rs} f_k^{rs}, \forall a \in A \tag{2d}$$

$$\bar{q}_{rs} \geq q_{rs}^{tran} \geq 0, \forall r \in R, s \in S \tag{2e}$$

where a is a link in the set A, x_a is flow in link a, $t_a(x_a)$ is link cost function in link a, R is origin node set, S is destination node set, K_{rs} is set of paths connecting OD pair rs, and f_k^{rs} is flow on path k between OD pair rs. $\delta_{a,k}^{rs}$ is 1 if link a is on path k between OD pair rs, and 0 otherwise.

The equation (2a) can be rewritten as

$$\begin{aligned}\min . Z(\mathbf{x},\mathbf{q},\mathbf{q}^{tran}) &= \sum_{a\in A}\int_0^{x_a} t_a(\omega)\,d\omega + \frac{1}{\theta}\sum_{r\in R}\sum_{s\in S} q_{rs}^{tran}\ln q_{rs}^{tran} \\ &+\frac{1}{\theta}\sum_{r\in R}\sum_{s\in S} q_{rs}\ln q_{rs} + \sum_{r\in R}\sum_{s\in S}\left(c_{rs}^{tran}-\frac{1}{\theta}\Psi_{rs}\right)q_{rs}^{tran}\end{aligned} \tag{3}$$

This optimization programs can be solved easily and efficiently by Frank-Wolfe method or Partial Linearization method.

3. INPUT DATA

We applied this combined modal split/assignment model to TMA. There are so many railway lines and complicated road networks in TMA, so we make best use of GIS (Geographic Information System) data. GIS-based transportation models have realistic representation of multi-modal transportation network, increased likelihood of database integrity after updates, effective user interfaces, and graphic display of model results (Miller and Storm, 1996).

3.1. Zoning System and O-D matrices

We estimated O-D matrices from TMA Person Trip (PT) survey in 1998, and Road Traffic Census OD survey in 1994. We used the departure time based OD. Zone size is PT Medium-size zone, which divides TMA into 144 zones (See Figure 2). Average area of Medium-size zones is about 100 km^2.

Car OD and transit OD are based on PT survey. Freight OD is based on Road Traffic Census. We calculate the model in each one-hour but we don't consider the residual OD for the simplicity.

3.2. Railway Network

We made railway network from the background data of Digital Road Map. This background data has only spatial information, so we add the various information such as kind of railway company. We also add transfer links and boarding links and egress links to make this network available in assignment model.

Table 1 shows the number of links and nodes in railway network. This network includes all the railways and stations in TMA. Figure 3 shows that railway network is very dense in this area.

Table 1. Railway Networks in TMA

	Station (each line)	Directed link
#	1654	4902

We add the constant fare cost on boarding links and distance-proportional fare on the line hole link. The line hole travel time is calculated by timetables. The fare is converted into travel time terms by value of time.

In order to consider different evaluations on in-vehicle time, access time, egress time, and transfer time, we put weights on access time, egress time, and transfer time. This conversion is based on the parameter estimated by Yai *et al.* (1997). They made railway route choice model in TMA by the multinomial probit with structured covariance. According to their estimation results, the value of in-vehicle cost and in-vehicle time is 11.9 ¥/min, and the trade-off ratio between access time and in-vehicle time is 1.83 and so forth. We use these variables in the conversion.

If you want to create the railway model completely in this area, you should distinguish the rail service class, such as express, rapid, and local train, and should set all the cost of transfer link properly. However, this task is very time consuming, so we use average travel time if there are more than one rail service classes in one link, and typical transfer cost.

We should confirm the reliability of this railway networks. Therefore, we at first make a transit assignment, by PT rail OD and this network. We used probit-based loading model (Sheffi, 1985) for this assignment. We cannot neglect the overlapped relation between pair of alternatives in the route choice behavior, because railways network is very dense in TMA. The logit-based loading model is not appropriate in this case.

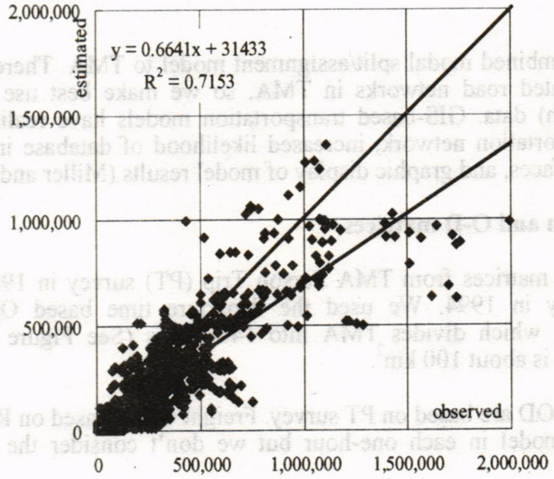


Figure 1. Estimated vs observed link flows in railways network

The assignment results are compared with the observed link flows by the Mass Transit Passenger Survey. The comparison of daily link flows is shown in Figure 1. The correlation coefficient *R* is 0.85, and *RMSE* is 182,717. The underestimate in larger link flow area can be partly due to the neglect of the intra-zonal trips.

We use the average minimum cost calculated by this probit assignment model as c_{rs}^{tran} in the equation (2a).

3.3. Automobile Model

Okuhira *et al.* (2000) constructed the fixed-demand network assignment model in TMA. We use the same network, link cost functions and road-related parameters as their model did. Their model reproduced the current road situation properly. The correlation coefficient *R* was 0.73 between estimated and observed link flows, and 0.66 between estimated and observed link velocity in the peak period.

Table 2. Road Networks in TMA

	node	link	dummy link
#	10692	22911	1324

Table 2 and Figure 4 show the road networks in TMA. This network has 2-level hierarchy. The network within 40km of central Tokyo is relatively dense, and the other is coarse.

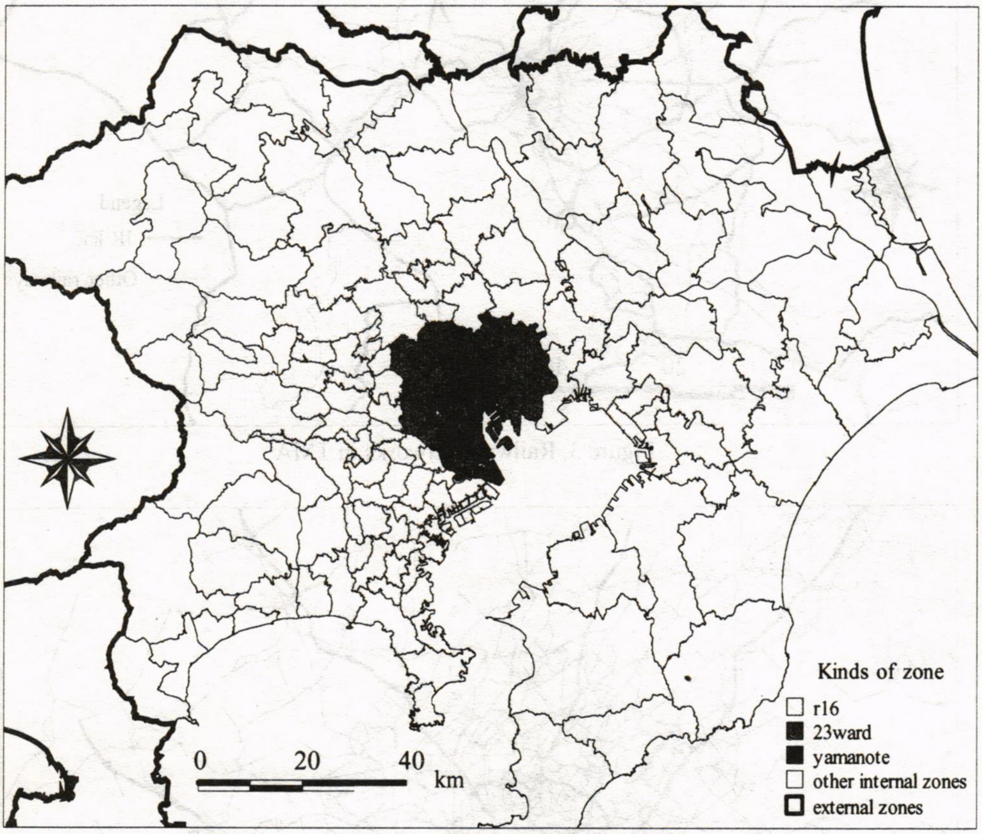


Figure 2. Zoning System

Figure 3. Railway Networks in TMA

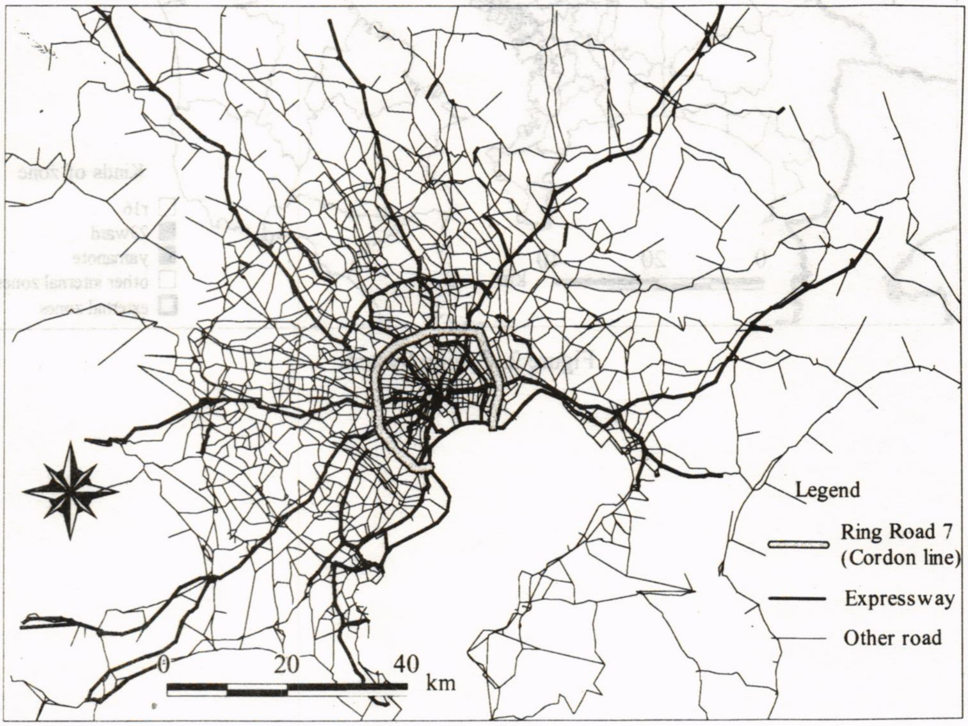


Figure 4. Road Networks in TMA

4. PARAMETER ESTIMATION

4.1. Estimation Method

We estimate the parameters in the mode split model (1) in this section. Kawakami and Mizokami (1986) proposed a method to simultaneously determine the parameters of mode choice and equilibrium traffic flow. Hicks and Abdel-aal (1998), Boyce and Zhang (1997) and Abrahamsson and Lundqvist (1999) showed some other methods of parameter estimation. In this paper, we use a simple method, that is, sequential estimation method.

At first, we temporarily assign automobile OD to road networks and get the minimum travel cost by automobile between each OD pair. Similarly, we assign the transit OD to transit network and get the minimum travel cost by transit. Then using both travel costs we estimate the parameters in logit model.

The travel cost here includes the monetary cost converted into minute terms by the value of time. We assume that value of time is 50 ¥/min. There are many toll roads in TMA and toll is converted into time. The transit fare is also converted into time.

4.2. Dummy variables

At First, we define "yamanote zone", "23ward zone", and "r16 zone" as shown in Figure 2. Roughly speaking "yamanote zone" is within the railway yamanote line, and "r16 zone" is within the Route 16. "23ward zone" belongs to the Tokyo 23 ward.

We use the dummy variables in (1), Ψ_{rs}, as following. L_yamanote is 1 if origin zone is yamanote zone, and 0 otherwise. A_yamanote is 1 if destination zone is yamanote zone, and 0 otherwise. L_23ward, A_23ward,L_r16, and A_r16 are defined similarly. These variables represent all factors other than the (generalized) travel-time difference, such as parking cost, trip purposes, and automobile ownership rate.

4.3. Estimation Results

We estimated the parameters in each time periods during 7a.m. and 7p.m. The result is shown in Table 3. Every parameter has correct signs and is statistically significant. Because of introducing dummy variable, we get good results. The correlation coefficient R is 0.92-0.99 between estimated and observed transit OD, and 0.85-0.92 between estimated and observed car OD (Figure 5). Changes of estimated dummy variables are shown in Figure 6. If these parameters are high, the transit will be preferred. The higher parameters of A_yamanote and A_23ward in the morning represent the transit morning rush hour to the central Tokyo. The higher parameters of L_yamanote and L_23ward in the evening represent the transit evening rush hour.

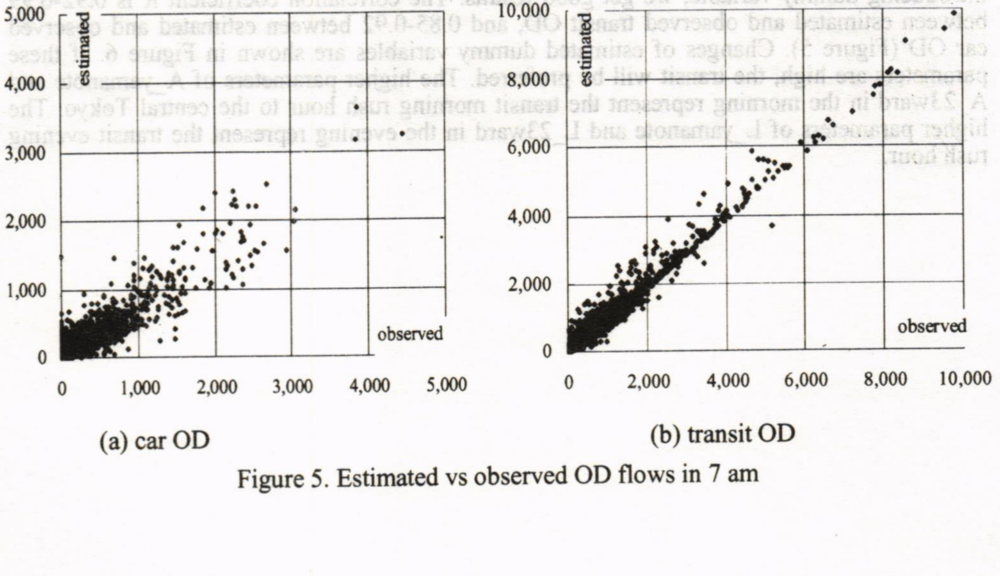
Table 3. Estimation Results of Modal-Split Model

time periods			7	8	9	10	11	12	13	14	15	16	17	18
Estimated parameters	θ	travel cost	0.0109	0.0069	0.0036	0.0051	0.0050	0.0039	0.0065	0.0068	0.0061	0.0061	0.0084	0.0061
		(/min)	(198.9)	(121.9)	(46.7)	(55.5)	(49.9)	(37.2)	(62.4)	(65.)	(67.8)	(74.8)	(128.8)	(96.)
	Ψ	L_yamanote	0.06	-0.50	-0.78	-0.27	0.47	0.86	1.23	1.57	1.86	1.93	2.64	2.88
		(8.)	(-71.1)	(-91.8)	(-28.2)	(45.8)	(79.4)	(111.)	(143.1)	(196.1)	(232.4)	(372.7)	(413.7)	(426.6)
		L_23ward	0.38	0.10	0.10	0.21	0.51	0.61	0.76	1.02	1.18	1.37	1.74	1.77
		(61.)	(16.5)	(12.2)	(22.5)	(48.1)	(53.)	(65.9)	(88.)	(118.6)	(155.)	(234.9)	(243.1)	(249.9)
		L_r16	0.38	0.23	0.28	0.34	0.50	0.49	0.64	0.78	0.84	0.82	0.95	0.99
		(89.9)	(50.4)	(42.7)	(43.1)	(56.4)	(51.4)	(64.7)	(78.5)	(102.7)	(116.2)	(164.2)	(169.5)	(176.6)
		A_yamanote	3.20	3.14	2.77	2.40	1.93	1.59	1.31	0.92	0.37	0.04	0.08	-0.22
		(484.2)	(478.6)	(321.4)	(246.8)	(179.2)	(144.4)	(119.2)	(86.5)	(38.9)	(5.)	(11.7)	(-31.1)	(-27.3)
		A_23ward	2.06	1.85	1.63	1.38	1.09	0.96	0.72	0.51	0.14	0.04	0.21	0.09
		(308.2)	(271.)	(175.9)	(131.8)	(95.2)	(82.1)	(62.)	(45.5)	(14.)	(4.3)	(29.9)	(12.8)	(14.7)
		A_r16	0.96	0.93	0.87	0.84	0.68	0.71	0.51	0.48	0.19	0.18	0.37	0.27
		(198.)	(179.4)	(118.1)	(97.4)	(70.1)	(72.2)	(52.1)	(51.5)	(23.7)	(26.4)	(70.)	(53.)	(55.8)
		Constant	0.20	0.10	-0.32	-0.79	-0.96	-0.90	-0.89	-0.89	-0.34	-0.02	-0.35	-0.43
		(31.8)	(14.2)	(-30.)	(-64.6)	(-70.4)	(-62.3)	(-63.)	(-63.7)	(-28.6)	(-1.7)	(-43.6)	(-52.1)	(-52.1)
# of samples		N	9119	9189	8023	6817	6159	5736	5592	5734	6358	7346	8429	8707
Reproduction Accuracy of transit OD		R	0.99	0.99	0.97	0.94	0.92	0.93	0.95	0.95	0.95	0.96	0.97	0.98
		B	1.00	1.00	0.99	1.01	0.83	0.85	1.07	1.06	1.04	1.03	1.02	1.01
		A	-0.89	0.24	1.33	-1.09	3.57	2.11	-5.53	-4.75	-3.90	-3.76	-3.73	-1.05
		$RMSE$	101.83	116.96	88.83	79.96	75.34	66.41	76.49	75.86	84.81	86.89	102.92	99.44
Reproduction Accuracy of car OD		R	0.92	0.88	0.85	0.91	0.90	0.89	0.92	0.92	0.88	0.87	0.91	0.89
		b	0.72	0.63	0.56	0.65	0.78	0.79	0.69	0.68	0.62	0.60	0.67	0.64
		a	21.43	26.33	22.38	21.84	23.02	21.28	21.34	21.20	22.64	22.71	24.11	24.95
		$RMSE$	101.83	116.96	88.83	79.96	75.34	66.41	76.49	75.86	84.81	86.89	102.92	99.44

( ):t-statistics, *R*: correlation coefficient, *RMSE*: Root mean square error.

Regression equation: $y = a + b\,x$, y: estimated OD trip, x: observed OD trip,

a: y-intercept, b: regression coefficient.



(a) car OD

(b) transit OD

Figure 5. Estimated vs observed OD flows in 7 am

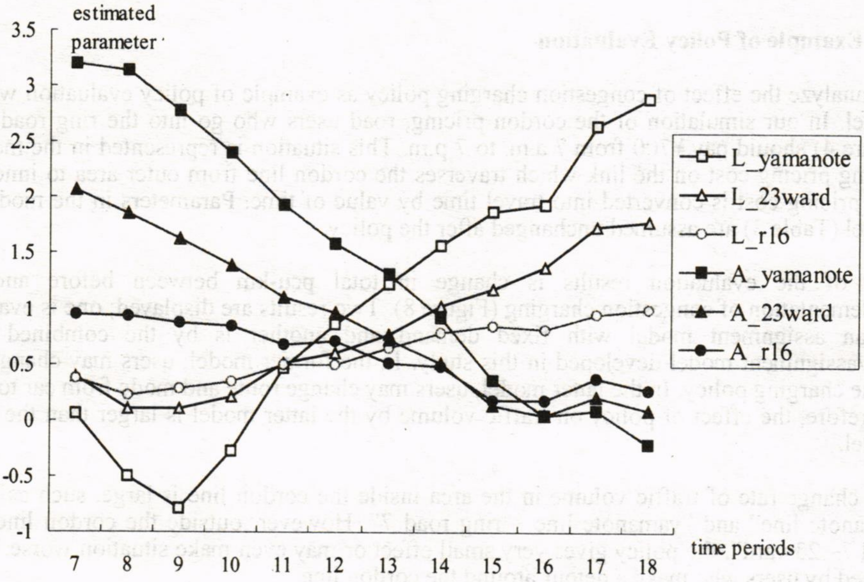


Figure 6. Changes of Dummy Variables

5. APPLICATION

5.1. Computation and Validation

We calculate the combined model using above-mentioned OD matrices, multi-modal network and estimated parameters for each one-hour period with Partial Linearization method. The increasing capabilities of computational platforms enable us to execute this large-scaled travel demand analysis.

We have to validate this model at first. As one of the validation, Figure 7 shows the change of objective function Z in (2a) as iteration grows. The value is monotonously decreasing, so this model seems to work properly.

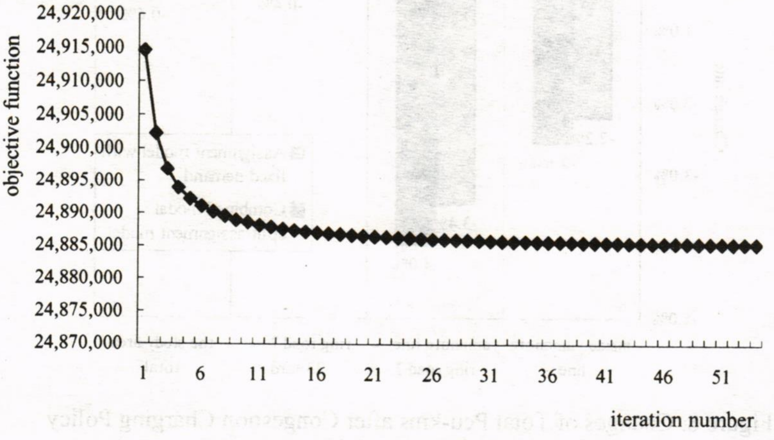


Figure 7. Convergence of objective function

5.2. Example of Policy Evaluation

We analyze the effect of congestion charging policy as example of policy evaluation with this model. In our simulation of the cordon pricing, road users who go into the ring road 7 (see Figure 4) should pay ¥700 from 7 a.m. to 7 p.m. This situation is represented in the model by adding pricing cost on the link which traverses the cordon line from outer area to inner area. The pricing cost is converted into travel time by value of time. Parameters in the modal split model (Table 3) are assumed unchanged after the policy.

One of the evaluation results is change in total pcu-km between before and after implementation of congestion charging (Figure 8). Two results are displayed; one is evaluation by an assignment model with fixed demand and another is by the combined modal split/assignment model developed in this study. In the former model, users may change route in the charging policy. In the latter model, users may change route and mode from car to transit. Therefore, the effect of policy on traffic volume by the latter model is larger than the former model.

The change rate of traffic volume in the area inside the cordon line is large, such as "inside yamanote line" and "yamanote line ~ ring road 7". However, outside the cordon line; "ring road 7~ 23ward", the policy gives very small effect or may even make situation worse. This is caused by users who make a detour around the cordon line.

In this study, the difference between fixed demand model and combined model is small. This is due to the small value of parameter θ in Table 3. If this value were bigger, the change rate would be larger.

For road pricing evaluations, there are other assignment models trying to tackle the "fixed" demand problem, such as elastic assignment or the matrix capping technique, without treating the modal split explicitly (Rogers, 1991; White *et al.*, 1995). Our combined model is theoretically superior to these simple models because our model deals with users' behavior explicitly. The empirical comparisons between these simple models and our combined model will be interesting.

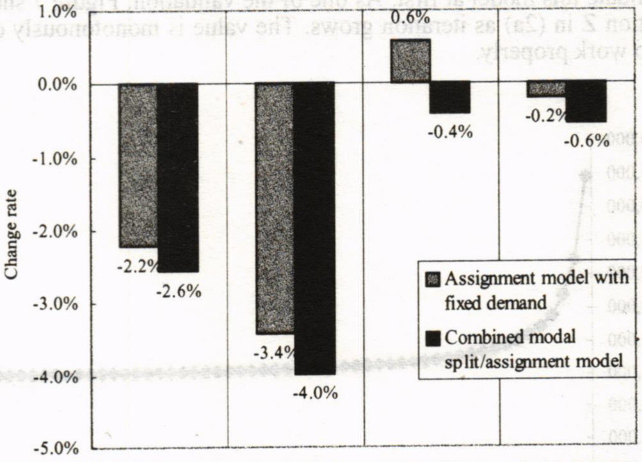


Figure 8. Changes of Total Pcu-kms after Congestion Charging Policy

6. CONCLUSION

In this study, we built a combined modal split/assignment model for the Tokyo Metropolitan Area (TMA), and used for simple policy evaluation. First, the equivalent mathematical problem was shown, and road and railway network in TMA constructed in GIS data. Then the reproduction accuracy of the model was checked and we estimate the parameters of modal split model for each one-hour period. Finally, the combined model was calculated and the congestion charging policy evaluated.

Much the further research is needed for a reliable evaluation of congestion charging policy in Tokyo. This model has only one user class, but the captives should be treated separately. Further challenging model developments, such as inclusion of departure time choice will be useful.

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