Evaluation of Road Pricing Policy with Semi-Dynamic Combined Stochastic User Equilibrium Model

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This study analyzes the effect of road pricing policy using a model that 1) incorporates trip generation (i.e. activity choice), destination choice, mode choice, and route choice; 2) considers variations in hourly traffic conditions, including queue evolution; and 3) approximately reproduces the trip chain along the time axis. An evaluation of road pricing policy in the Nagoya Metropolitan Area shows that the policy can improve the environment by reducing the number of car trips that are taken. At the same time, it greatly reduces the number of visitors to the city center by promoting a destination change and only a small shift from cars to railways.

Keywords: Road Pricing, Transport Demand Forecasting, Combined Stochastic User Equilibrium Model

1. Introduction

Over-dependence on the automobile has led to chronic traffic congestion and air pollution in Nagoya City. Improvements of road and railway networks as well as transportation or travel demand management (TDM) have implemented to achieve more appropriate automobile usage. Recently, considerable attention has focused on one TDM policy, road pricing, which has proved very successful in Singapore and London. Because travelers must pay to use the roads, they may change their route, mode, destination, departure time, and even choose not to travel. Such changes in traveler behavior also affect the conditions of the road network. Evaluating road pricing policy requires a model that can calculate the equilibrium state of traffic supply and demand in the transportation network.

Many studies have used the equilibrium model to evaluate road pricing policy in urban areas. May and Milne [1] evaluate various road pricing systems in Cambridge (in the UK), including cordon-based, distance-based, time-based, and congestion-based charging. Santos [2] simulates cordon pricing in eight English towns. The model used in these studies, however, does not explicitly express traveler behavior because it uses an elastic assignment model. Maruyama and Sumalee [3] use an elastic demand model, even though they compare cordon-based and area-based charging using an innovative trip-chain equilibrium model. On the

other hand, Maruyama *et al*. [4] analyze the effects of road pricing in the Tokyo Metropolitan Area with a model that considers a traveler's mode choice, route choice, and both car and railway network congestion. Furthermore, de Palma *et al*. [5] take into account the departure time, mode choice, and route choice in their dynamic equilibrium simulator. Gentile *et al*. [6] utilize multi-class assignment in a multimodal network that includes trip generation, modal split, and route assignment. Although some of these studies expressed traveler behavior, none included destination choice. Yet, as noted above, road pricing policy yield a change in destination as well as route choice. In this study, we improve the evaluation model by introducing destination choice.

The objective of this study is to develop a combined user equilibrium model that includes activity choice and the time dimension—that is, a semi-dynamic combined stochastic user equilibrium model—and to evaluate road pricing policies in the transport network of a real metropolitan area. The model developed in this study has the following characteristics. First, the model considers traveler's activity choices (by integrating trip generation, destination choice, mode choice and route choice). Thus it is able to measure induced traffic by a change in traffic conditions. Traveler choice behavior is assumed to be expressed as a nested logit structure, which is based on random utility maximization theory. The developed model also allows for hourly variations in travel time resulting from both changes in traffic congestion and the

frequency of public transit services. Finally, the trip chain is approximated by computing in sequence the equilibrium state in each time period. For this purpose, we deal with activity related to staying (not traveling), intra-zonal O-D trips and walking trips. The model is formulated using a mathematical optimization approach, resulting in a unique solution that is the equilibrium state. These characteristics of the model make it possible to evaluate road pricing policies (in this study, cordon-based road pricing) in detail.

2. Model Formulation

2.1. Semi-dynamic Traffic Assignment Model with Queue Evolution

The semi-dynamic traffic assignment model with queue evolution, as formulated by Akamatsu *et al*. [7], is based on certain assumptions. First, the time period T (in this study, T is set to one hour) is longer than any travel time between an origin-destination (O-D) pair, and the traffic state in each time period is assumed to be static. Traffic state transitions occur only at transitions between time periods. Second, each link consists of an un-congested segment and a congested segment. The former is the segment representing vehicular flow, and the passage time is expressed by the usual link performance function. The latter is an outflow terminal node with a vertical queue. Consequently, a state transition can be expressed by equation (1) and the travel time on a link by equation (2).

$$\begin{cases} X_a^T = X_a^{T-1} + x_a^T - \mu_a & if \quad X_a^T > 0 \\ X_a^{T-1} + x_a^T \le \mu_a & if \quad X_a^T = 0 \end{cases} \quad (1)$$

where x_a^T is the inflow rate on link a in time period T, X_a^T is the queue on link a in T, X_a^{T-1} is the queue formed in the previous time period (and treated as a constant in T), and μ_a is the maximum discharge rate calculated from the potential capacity of link a.

$$t_a^T = t_a(x_a^T) + \max.(X_a^{T-1} + x_a^T - \mu_a, 0)/\mu_a \quad (2)$$

where t_a^T is the travel time on link a in time period T including time lost waiting in any queue, and $t_a(\cdot)$ is the link performance function (i.e. the BPR function).

The time-dependent traffic state in time period T is formulated as an equivalent minimization problem. Each time-dependent traffic state is achieved independently of other time periods on condition that the flow remnants are given as constants. In addition, x_a^{T*} in the equilibrium state is calculated by a normal solution algorithm (e.g. the Frank-Wolf method) substituting $t_a(\cdot)$

as calculated with the usual link performance function with t_a^T as given by equation (2). X_a^{T*}, calculated using equation (1), is treated as the flow remnants on link a in the next time period if it is non-zero.

2.2. Traveler Behavior

We assume that the behavior of travelers in each time period is expressed as the nested logit structure shown in Figure 1. This structure considers activity choice, destination choice, mode choice, and route choice behavior.
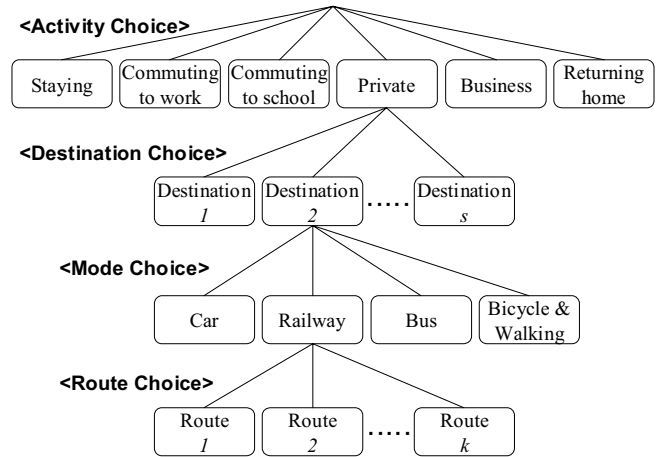

Figure 1. Structure of the traveler choice process in each time period

2.3. Formulation of Semi-dynamic Combined Stochastic User Equilibrium Model

The travel time on each link in the road network is expressed by equation (2). In addition, prices (such as expressway tolls) are converted into time terms according to the value of time for each activity. Link travel time varies according to the inflow rate on the link and the path flow, which is the result of traveler behavior. At the same time, the generalized travel time in the behavioral model varies according to the link travel time. Thus, we need to seek an equilibrium state between demand and supply in each time period T. This equilibrium state can be obtained by solving the following equivalent convex minimization problem—the Semi-dynamic Combined Stochastic User Equilibrium Model which is one of a multi-class user equilibrium model. Since each time-dependent traffic state is achieved independently of the other time periods on condition that the flow remnants and the number of people present at each location in each zone are given constants, the expression is simplified by omitting from the following equation the subscript representing a specific time period (T).

$$\min. Z = \sum_a \int_0^{x_a} t_a(\omega)d\omega + \sum_{i,a} x_a^i\, p_a \big/ \tau^i$$

$$+ \sum_a \left\{\max.(X_a^{T-1} + x_a - \mu_a, 0)\right\}^2 \big/ (2\mu_a)$$

$$+ \sum_{i,rs,m,k} \frac{1}{\theta_1^{i,m}} f_{m,k}^{i,rs} \ln(f_{m,k}^{i,rs} / q_m^{i,rs}) + \sum_{i,rs,m',k} f_{m',k}^{i,rs}\, C_{m',k}^{i,rs}$$

$$+ \sum_{i,rs,m} \frac{1}{\theta_2^i} q_m^{i,rs} \ln(q_m^{i,rs} / Q_{rs}^i) + \sum_{i,rs,m} q_m^{i,rs}\, V_m^{i,rs} \qquad (3a)$$

$$+ \sum_{i,rs} \frac{1}{\theta_3^i} Q_{rs}^i \ln(Q_{rs}^i / O_r^i) + \sum_{i,rs} Q_{rs}^i\, V_s^i$$

$$+ \sum_r \frac{1}{\theta_4^l} [O_{r,l}^0 \ln(O_{r,l}^0 / N_{r,l}) + \sum_i O_r^i \ln(O_{r,l}^i / N_{r,l})]$$

$$+ \sum_{i,r,l} O_{r,l}^i\, V_{r,l}^i$$

subject to $x_a = \sum_{i,rs,k,a} f_{m,k}^{i,rs} \cdot \delta_{a,k}^{i,rs}, \quad \forall a \qquad (3b)$

$$\sum_i x_a^i = x_a, \quad \forall a \qquad (3c)$$

$$\sum_k f_{m,k}^{i,rs} = q_m^{i,rs}, \quad \forall i, rs, m \qquad (3d)$$

$$\sum_m q_m^{i,rs} = Q_{rs}^i, \quad \forall i, rs\; s \qquad (3e)$$

$$\sum_s Q_{rs}^i = O_r^i, \quad \forall i, r \qquad (3f)$$

$$\sum_l O_{r,l}^i = O_r^i, \quad \forall i, r \qquad (3g)$$

$$\sum_i O_{r,l}^i + O_{r,l}^0 = N_{r,l}, \quad \forall r, l \qquad (3h)$$

$$f_{m,k}^{i,rs} \geq 0, \quad q_m^{i,rs} \geq 0, \quad Q_{rs}^i \geq 0,$$
$$O_r^i \geq 0, \quad O_{r,l}^i \geq 0, \quad O_{r,l}^0 \geq 0 \qquad (3i)$$

where $f_{m,k}^{i,rs}$ is the path flow by each mode for each activity, $q_m^{i,rs}$ is the O-D trips by each mode for each activity, Q_{rs}^i is the O-D trips for each activity, O_r^i is the number of trips generated by each activity, $O_{r,l}^i$ is the number of trips generated by each activity in each location, $O_{r,l}^0$ is the number of people staying at the same location, $N_{r,l}$ is the number of people who stayed in the same zone or made a trip in the previous time period, $\delta_{a,k}^{i,rs}$ is 1 if the link is on k th path between an O-D pair by each mode and 0 otherwise, p_a is the price or charge on the link, τ^i is the value of time for each activity, $C_{m,k}^{i,rs}$ is the generalized travel time on the k th

path between an O-D pair by each mode for each activity, $V_m^{i,rs}$, V_s^i and $V_{r,l}^i$ are systematic components of each choice, and $\theta_1^{i,m}$, θ_2^i, θ_3^i and θ_4^l are scale parameters.

It can be proved easily that this problem has a unique solution under these conditions (3b-i). The Kuhn-Tucker conditions for the problem lead to the aforementioned nested logit model with stochastic user equilibrium conditions.

$$f_{m,k}^{i,rs} = \frac{\exp[-\theta_1^{i,m} C_{m,k}^{i,rs}]}{\sum_k \exp[-\theta_1^{i,m} C_{m,k}^{i,rs}]} q_m^{i,rs} \qquad (4a)$$

$$q_m^{i,rs} = \frac{\exp[-\theta_2^i (V_m^{i,rs} + S_m^{i,rs})]}{\sum_m \exp[-\theta_2^i (V_m^{i,rs} + S_m^{i,rs})]} Q_{rs}^i \qquad (4b)$$

$$S_m^{i,rs} = -\frac{1}{\theta_1^{i,m}} \ln \sum_k \exp[-\theta_1^{i,m} C_{k,m}^{i,rs}] \qquad (4c)$$

$$Q_{rs}^i = \frac{\exp[-\theta_3^i (V_s^i + S_{rs}^i)]}{\sum_s \exp[-\theta_3^i (V_s^i + S_{rs}^i)]} O_r^i \qquad (4d)$$

$$S_{rs}^i = -\frac{1}{\theta_2^i} \ln \sum_m \exp[-\theta_2^i (V_m^{i,rs} + S_m^{i,rs})] \qquad (4e)$$

$$O_{r,l}^i = \frac{\exp[-\theta_4^l (V_{r,l}^i + S_r^i)]}{1 + \sum_i \exp[-\theta_4^l (V_{r,l}^i + S_r^i)]} N_{r,l} \qquad (4f)$$

$$S_r^i = -\frac{1}{\theta_3^i} \ln \sum_s \exp[-\theta_3^i (V_s^i + S_{rs}^i)] \qquad (4g)$$

where $S_m^{i,rs}$, S_{rs}^i and S_r^i are inclusive values.

The partial linearization algorithm [8] can be used to efficiently solve this problem. Even though the problem includes a path-flow entropy term, the model can be applied to large networks using entropy decomposition as shown by Akamatsu [9]. Figure 2 shows a more practical calculation procedure for achieving equilibrium traffic states in each time period. As this demonstrates, the equilibrium state in each time period is determined from traveler activity and from traffic conditions in the previous time period, and from the zone characteristics. Note that in the first time period only those dwelling within each zone are treated as being present in the zone. In this way, the model can represents the trip chain along the time axis through the equilibrium states in each time period.
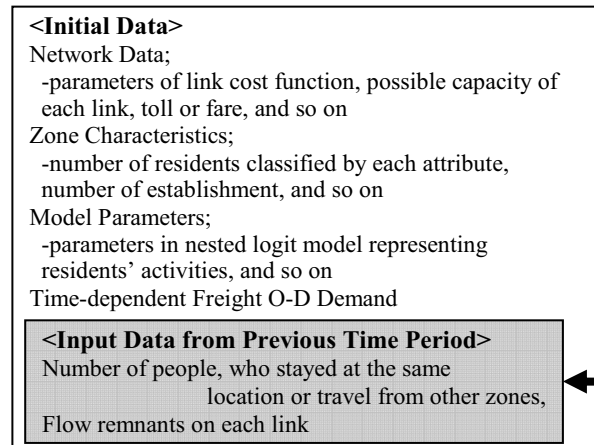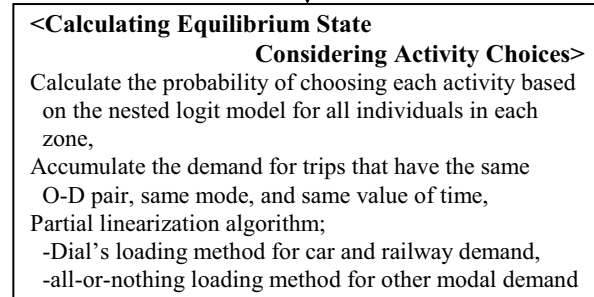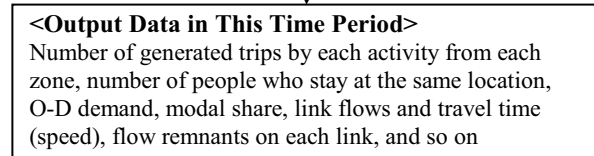
INPUT

<Initial Data>
Network Data;
  -parameters of link cost function, possible capacity of
  each link, toll or fare, and so on
Zone Characteristics;
  -number of residents classified by each attribute,
  number of establishment, and so on
Model Parameters;
  -parameters in nested logit model representing
  residents' activities, and so on
Time-dependent Freight O-D Demand

<Input Data from Previous Time Period>
Number of people, who stayed at the same
             location or travel from other zones,
Flow remnants on each link

CALCULATION

**<Calculating Equilibrium State
               Considering Activity Choices>**
Calculate the probability of choosing each activity based
  on the nested logit model for all individuals in each
  zone,
Accumulate the demand for trips that have the same
  O-D pair, same mode, and same value of time,
Partial linearization algorithm;
  -Dial's loading method for car and railway demand,
  -all-or-nothing loading method for other modal demand

OUTPUT

<Output Data in This Time Period>
Number of generated trips by each activity from each
zone, number of people who stay at the same location,
O-D demand, modal share, link flows and travel time
(speed), flow remnants on each link, and so on

**Figure 2. Calculating equilibrium states
               in each time period**

3. Application to Nagoya Metropolitan Area

This paper briefly describes the developed model's application to the Nagoya Metropolitan Area. Please refer to our previous studies for details [10, 11].

3.1. Input Data and Given Parameters

In order to apply the developed model to an actual situation, in this case the Nagoya Metropolitan Area, the model parameters must be estimated. Travelers behavior in this area was obtained from the 4th Nagoya Metropolitan Area Person Trip (PT) Survey conducted in 2001. The parameters are estimated based on this PT survey data by means of the maximum likelihood method.

Traffic conditions reported by the PT survey are assumed to correspond to the stochastic traffic equilibrium state. The average hourly travel time on

every road link is calculated from a 'Link Cost Table' developed using probe-vehicle data gathered in the Nagoya Metropolitan Area [12]. The average time per hour of travel by railway and bus is calculated from the timetables. Estimates of model parameters, as well as the analysis, are based on the PT minimum size zone, in which Nagoya City is divided into 258 zones with an average area of 1.25 km^2. Data representing zone characteristics (such as area and population) are obtained using Geographical Information Systems. We also consider intra-zonal O-D trips, the level-of-service of which is set to zero for car and bicycle travel and walking. Vehicle occupancy is assumed to be 1.0. The positive scale parameter for a car in route choice $\theta_1^{i,m}$ is set to 0.5 (1/minute). For drivers, the value of time is set to 83.4 JPY per minute for the activities of commuting to work and to school and business travel. The corresponding value for private trips and returning home is 43.9 JPY per minute. These values are also estimated based on the 4th Nagoya Metropolitan Area PT survey data preparatory to estimating the model parameters. The inclusive value of the driver's route choice is calculated from the link weight value of Dial's algorithm [13].

3.2. Estimation of Model Parameters

3.2.1. Route Choice and Mode Choice. First, we estimate the parameters of route choice and mode choice for each activity. The estimation results are shown in Table 1. The route choice model considers only car and railway travel because of the work involved in developing alternative route data. The parameters of the route choice model are common to all activities.

Level of service, socio-economic characteristics and parking charges are adopted as explanatory variables. Every parameter has the expected sign and is statistically significant. The calculated value of in-vehicle time for railway travel is 22.1 JPY per minute, and out-of-vehicle time is valued at 36.5 JPY per minute. Intuitively, these values seem appropriate. The calculated value of in-vehicle time for bus travel is 10.2 JPY pre minute and out-of-vehicle time is valued at 6.3 JPY per minute. Intuitively, these values seem low. This may be due to the flat fare system used by urban transport services in Nagoya City. For the mode choice for private and business trips, the model considers influence of the pre-trip mode, which is the same as in the previous trip. Similarly, a dummy, which is given a value of 1 when the selected mode is the same as that for leaving home, is introduced in the mode choice for returning home.

3.2.2. Destination Choice. Next, we estimate the parameters of the destination choice model for each activity. In this case, the destination choice for returning home is excluded because the destination is fixed (the home zone). The parameters are estimated from a set of

twenty randomly selected alternative choices, since the true number of alternatives is huge (about 300 zones).

Some zone characteristics are adopted as explanatory variables. A 'Same zone dummy' is introduced for intra-zonal O-D trips. The estimation results are shown in Table 2. Every parameter has the expected signs and is statistically significant. Since the scale parameters are smaller than those in the mode choice model, the assumption of a nested logit structure is satisfied. In the destination choice for commuting to school and for private trips, the estimated distance between the O-D pairs in addition to the inclusive value, is estimated is negative because the chosen destinations tend to be nearby.

3.2.3. Activity Choice. Finally, we estimate the parameters of the activity choice model in each location (Home, Workplace/Study place, Other place). The activity choices are appropriately set for each location, occupation and the activity history. For instance, "commuting to work" is set only for a worker who has not arrived at his/her workplace. In addition, since home-to-work and home-to-school trips are daily habitual daily activities, it is assumed that these activity choices are not influenced by accessibility (inclusive value). Thus, the scale parameter for home-to-work and home-to-school trips is set to zero.

Socio-economic characteristics and current activity duration are adopted as explanatory variables. The estimation results are shown in Table 3. Every parameter has the expected signs and is statistically significant. Since the scale parameters are smaller than those in the destination choice model, the assumption of a nested logit structure is satisfied. In these models, it is the case that the temporal utility profiles of activities [14, 15] are expressed by dummy variables according to the specific time period.

Table 1. Estimation results of route choice and mode choice

<Route Choice Model>

Mode	Variable	
Car	Scale parameter	0.50
	VOT（JPY/min）[Commuting to Work,Business, Commuting to School]	83.4
	VOT（JPY/min）[Private,Returnning Home]	43.9
Railway	Scale parameter	0.322
	In-vehicle time(hour)	-9.84
	Out-of-vehicle time(hour)	-16.2
	Cost(100JPY)	-0.742
	# of transfers	-0.322
	Access distance(km)	-1.92
	Egress distance(km)	-1.86
	Representative station dummy*1	0.417

*1:Representative station dummy is 1 if the station of access side is transfer station or express stop station, otherwise is 0

*2:Pre-trip mode dummy is 1 if the mode is same one in pre-trip, otherwise is 0.

*3:Out of home mode dummy is 1 if the mode is same one in trip of leaving home, otherwise is 0.

*4:Average parking charge in destination that is calculated from the PT data (monthly charge; commuting to work, hourly charge; private and business)

<Mode Choice Model>

Mode	Variable	Activity				
		Commuting to Work	Commuting to School	Private	Business	Returnning Home
	Scale parameter	0.095	0.091	0.092	0.079	0.073
	Pre-trip mode dummy*2	-	-	2.32	2.49	-
	Out of home mode dummy*3	-	-	-	-	4.44
Car	Parking charge(1,000JPY)*4	-0.787	-	-1.02	-1.70	-
	Driver's license	2.56	2.15	1.63	2.75	-
	Vehicle owned	3.27	-	2.18	-	-
	Male dummy	0.685	-	-	0.927	-
Railway	Constant	4.79	2.87	1.47	0.71	-0.552
	Age dummy _over 65	-	-	0.855	-	-
Bus	Constant	4.39	1.29	1.50	0.55	1.23
	In-vehicle time(hour)			-2.94		
	Out-of-vehicle time(hour)			-1.81		
	Cost(100JPY)			-0.480		
	Access distance(km)			-0.546		
	Egress distance(km)			-0.614		
	Age dummy _over 65	-	-	1.40	-	-
Bicyle & Walking	Constant	6.44	6.03	4.21	2.86	2.01
	Travel time(hour)			-7.34		
	Number of samples	14,698				
	Log likelihood at zero	-23,795.6				
	Log likelihood at convergence	-9,275.8				
	Adjusted McFadden's Rho-squared	0.608				

** All estimated values are different from 0 with 5% statistical significant level.

Table 2. Estimation results of destination choice

Variable	Activity			
	Commuting to Work	Commuting to School	Private	Business
Scale parameter	0.080	0.056	0.057	0.078
log Area(ha)*1	1.00	1.00	1.00	1.00
log Worker per area(person/ha)	-0.158	-	-	-
log Employee per area(person/ha)	0.927	-	0.485	0.782
log Student per area(person/ha)	-	0.315	-	-
log Shop per area(office/ha)	-	-	0.296	-
log Office per area(office/ha)	-	-	-0.334	0.118
log Factory per area(office/ha)	-	-0.459	-0.169	-
log School and Hospital per area(office/ha)	-	0.476	0.329	-
log extension of road per area(m×km/ha)	0.158	-	-	-
log O-D distance(km)	-	-	-1.87	-
log O-D distance_age under 15 (km)*2	-	-2.35	-	-
School dummy*3	-	0.390	-	-
Shop dummy*3	-	-	0.552	-
Same zone dummy[in Nagoya city]*4	-1.91	-2.25	-3.06	-1.54
Same zone dummy[out of Nagoya city]*4	-3.46	-4.03	-5.14	-2.11
Number of samples	4,019	1,493	5,925	1,478
Log likelihood at zero	-13,446.2	-4,442.4	-19,425.8	-5,045.1
Log likelihood at convergence	-6,335.7	-1,213.1	-4,317.6	-2,207.3
Adjusted McFadden's Rho-squared	0.528	0.725	0.777	0.561

*1:This parameter is set 1.0 because area of zone is treated as the standard scale variable.

*2:O-D distance specific to under 15 years old.

*3:This dummy is 1 if corresponding facilities include in destination zone that is calculated from GIS, otherwise is 0.

*4:This parameter is corrected the sampling bias.

** All estimated values are different from 0 with 5% statistical significant level.

Table 3. Estimation results of activity choice

<Home>

Variable	Activity			
	Commuting to Work	Commuting to School	Private	Business
Scale parameter[Privaste,Business]	-	-	0.009	
Constant	-3.91	-7.24	-7.31	-9.78
log(Current activity duration+1.0)(hour)	0.314	1.90	-0.051	-0.610
Worker_dummy	-	-	-	1.80
Time period dummy_8-11_worker	-	-	0.206	-
Time period dummy_15-19_worker	-	-	0.658	-
Time period dummy_15-19_student	-	-	0.874	-
Time period dummy_8-16_non-worker	-	-	0.692	-
Time period dummy	Details are omitted for the space saving.			
Number of samples	20,712			
Log likelihood at zero	-216,568.8			
Log likelihood at convergence	-29,769.4			
Adjusted McFadden's Rho-squared	0.862			

** All estimated values are different from 0 with 5% statistical significant level.

<Work place/Study place>

Variable	Activity		
	Private	Business	Returnning Home
Scale parameter		0.008	
Constant	-8.25	-6.08	-7.41
log(Current activity duration+1.0)(hour)	0.064	-1.45	-
log Current activity duration(hour) [arrival before 16]	-	-	0.860
log Current activity duration(hour) [arrival after 17]	-	-	1.08
Male-worker dummy	-	1.66	-
Time period dummy_12-14_female-worker	-	-	1.64
Time period dummy_15-16_female-worker	-	-	1.32
Time period dummy_15-17_female-worker	1.78	-	-
Time period dummy_12-14_student	-	-	1.91
Time period dummy_15-16_student	-	-	2.84
Time period dummy_15-17_student	1.57	-	-
Time period dummy	Details are omitted for the space saving.		
Number of samples	6,034		
Log likelihood at zero	-72,026.0		
Log likelihood at convergence	-15,669.0		
Adjusted McFadden's Rho-squared	0.782		

** All estimated values are different from 0 with 5% statistical significant level.

<Other Place>

Variable	Activity				
	Commuting to Work	Commuting to School	Private	Business	Returnning Home
Scale parameter			0.011		
Constant	-4.27	-3.54	-4.54	-5.31	-1.84
log(Current activity duration+1.0)(hour)	-0.916	-1.28	-	-	-
log Current activity duration(hour) [arrival by private purpose]	-	-	-0.049	-3.10	-0.923
log Current activity duration(hour) [arrival by business purpose]	-	-	-0.989	-1.25	-1.34
Worker dummy	-	-	-	1.96	-
Time period dummy_10-12_non-worker	-	-	0.408	-	0.426
Time period dummy_13-16_non-worker	-	-	0.515	-	0.699
Time period dummy_10-12_over 65 age	-	-	-	-	0.271
Time period dummy	Details are omitted for the space saving.				
Number of samples	6,619				
Log likelihood at zero	-19,074.1				
Log likelihood at convergence	-11,961.9				
Adjusted McFadden's Rho-squared	0.371				

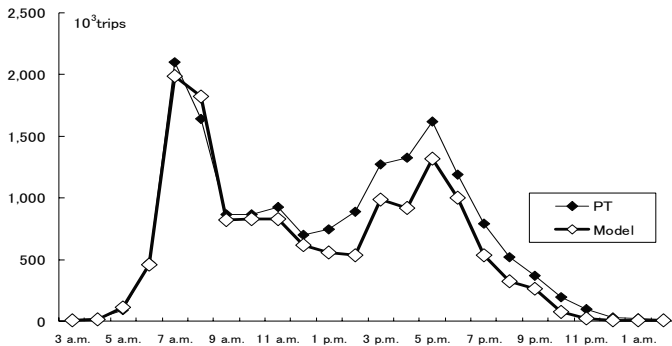** All estimated values are different from 0 with 5% statistical significant level.

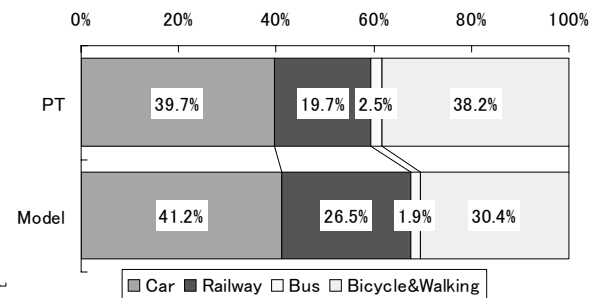**Figure 3. Total numbers of trips generated**

Figure 4. Modal share of Nagoya City

3.3. Model Validation

The model set up with the parameters estimated in the previous section was applied to the Nagoya Metropolitan Area. The road network consists of 22,466 links and 7,606 nodes. We use a BPR type link performance function with parameters recently estimated in Japan [16, 17]. Since freight data is not included in the PT survey data, this data is based on the Road Traffic Census O-D Survey of 1999. It is assumed that freight vehicles make trips between fixed O-D pairs and that the value of time

is 87.4 JPY per minute, as calculated by the Japan Society of Civil Engineers [16].

In order to validate traffic states, this study sets 3:00 a.m. as the time at which number of residents in each zone is determined. For the convergence condition of the equilibrium calculation, traffic in each level is assumed to change by less than 1% and the equilibrium calculation is done 5-8 times in each time period.

The total numbers of trips generated in each time period are shown in Figure 3. Overall trip generation is well replicated along the time axis, although systematic

underestimation after 1 p.m. is evident. One reasonable explanation for this tendency to underestimate the number of trips generated is that we assume travelers will not make more than one trip in each time period. As shown in Figure 4, the share of railway is overestimated even though the estimate for the share for cars is fairly good. Furthermore, with a correlation coefficient of 0.84 and a regression coefficient of 0.92, the reproducibility of the car link flow is relatively good.

These results largely validate the developed model for large-scale transportation planning, even though it tends to somewhat underestimate the total number of trips.

4. Evaluation of Road Pricing Policy

The developed model can serve as a primary analysis for evaluating cordon road pricing policy. Cordon road pricing is a system by which road users entering a cordoned area must pay a charge. By introducing a road pricing policy, road users will change their choice of route, mode, destination, departure time, and even the decision of whether to travel or not. The developed model considers activity choice, destination choice, mode choice and route choice. The departure time decision, which is a main effect of London's road pricing policy [18], is not considered due to model complexity. Such consideration is a task for future studies.

In order to compare the effect of various cordon areas and price levels in Nagoya City, the following cases of charging are introduced, with charging from 7:00 a.m. to midday.

- ➤ Case_0: No change.
- ➤ Case_1_700: Cordon area shown by inner line; Price level is 700 JPY
- ➤ Case_1_1500: Cordon area shown by inner line; Price level is 1,500 JPY
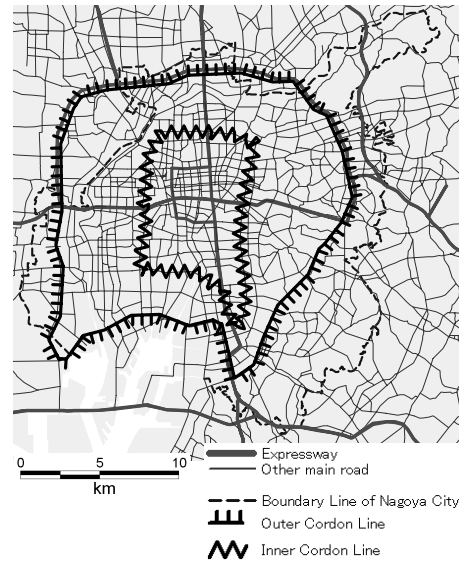- ➤ Case_2_700: Cordon area shown by outer line;

Figure 5. Cordon lines in case studies

Price level is 700 JPY

- ➤ Case_2_1500: Cordon area shown by outer line; Price level is 1,500 JPY

The inner and outer cordon boundary lines are shown in Figure 5. The inner line encloses the city center while the outer line encompasses most of Nagoya City. The price is converted into travel time by the value of time for each activity.

Figure 6 is a comparison of the number of trips attracted to Nagoya City. Every case with pricing shows little change from Case_0 (with no pricing) in the total number of trips, although the number of car trips is lower to some extent in all cases (in Case_1_700: -6%; in Case_1_1500: -10%; in Case_2_700: -7%; and in Case_2_1500: -12%). Figure 7 compares the number of trips to the city center. The total number of trips attracted to the city center is reduced by 7-11% in the Case_1 series, where the cordon is the inner line. In particular,
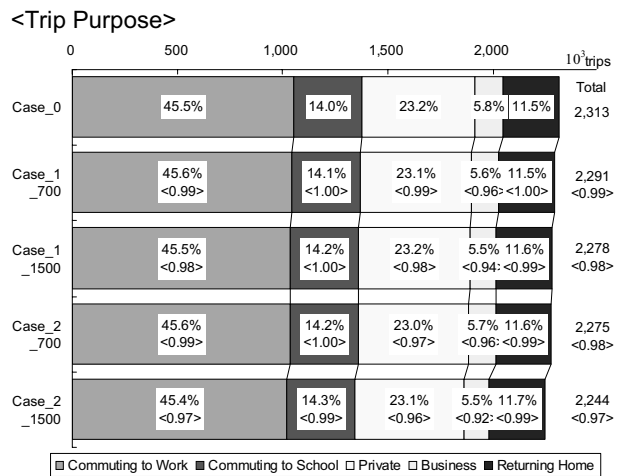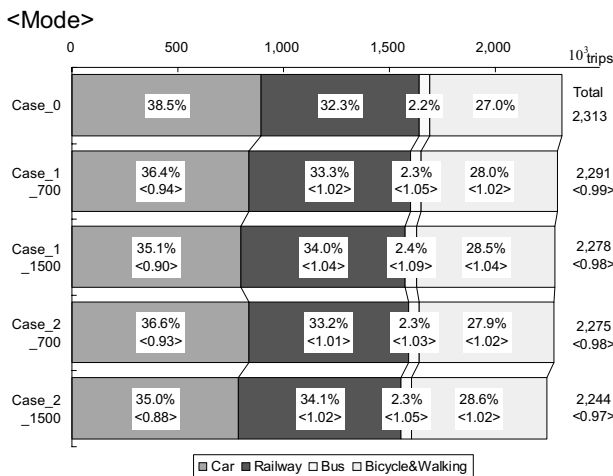
Note: figures in angle brackets denote the rate of change from case_0   .

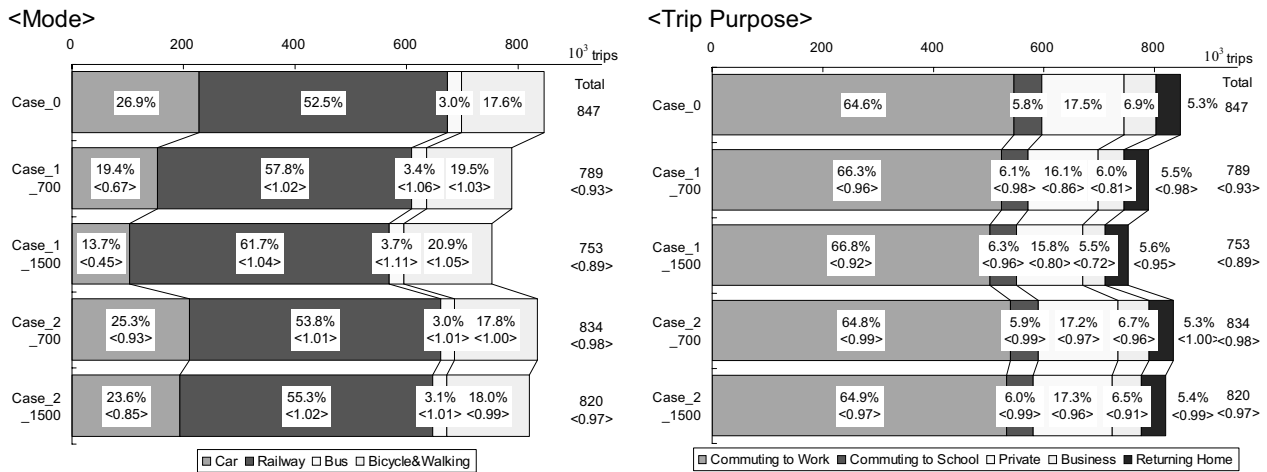**Figure 6. Number of trips attracted to Nagoya City**

Figure 7. Number of trips attracted to the City Center

Table 4. Changes in O-D trips

OD pattern			Case_1_700 / Case_0				Case_1_1500 / Case_0			
from		to	Total	Private	Car	Railway	Total	Private	Car	Railway
{1} City Center	⇒	{1}	0.97	0.96	**0.91**	1.00	0.96	**0.94**	**0.87**	1.00
	⇒	{2}	**0.93**	0.97	**0.82**	1.03	**0.90**	0.96	*0.74*	**1.05**
	⇒	{3}	**0.94**	1.01	**0.83**	1.01	**0.91**	1.03	0.76	1.01
{2} Inside Nagoya City (except for {1})	⇒	{1}	**0.89**	**0.75**	*0.54*	**1.07**	**0.83**	*0.66*	*0.25*	**1.12**
	⇒	{2}	1.04	1.04	1.05	1.04	**1.06**	**1.06**	**1.08**	**1.07**
	⇒	{3}	1.03	1.02	1.03	1.03	1.05	1.02	**1.05**	**1.06**
{3} Outside Nagoya City	⇒	{1}	**0.95**	*0.68*	0.59	1.00	**0.91**	*0.54*	*0.26*	1.01
	⇒	{2}	1.02	1.03	1.05	1.00	1.04	**1.05**	**1.09**	1.00
	⇒	{3}	1.00	1.00	1.00	1.00	1.00	1.00	1.01	1.00

Case_1_1500 leads to 55% fewer car trips. It turns out that within the city center where the railway network is sufficiently developed, the shift from car to railway is smaller than we expected, and the number of visitors for private and business is reduced sharply.

According to Table 4, which shows the changes in O-D trips, car trips from the outer city center ({2} and {3}) to the inner area ({1}) are reduced sharply compared to Case_0 (in Case_1_700: -55%; in Case_1_1500: -75%). As a result, the total number of private trips is much lower, even though more railway trips are made from within Nagoya City to the city center (in Case_1_700: 7%; in Case_1_1500: 12%).

Judging from the small shift from car to railway, the decisions to change destinations or not to travel arise frequently. As an example, changes in private trips to each zone are shown in Figure 8. It is clear that the main choices for alternative destinations are in the fringe areas, with more trips in the zones adjacent to the cordon. In addition, the larger the area surrounded by the cordon, the larger the number of zones influenced by this behavior. This suggests that, to increase the number of visitors to the city center, road pricing policy should be implemented together with other policies, such as discounted railway fares.

Table 5 shows the effects on road traffic and the environment. The vehicle kilometers traveled within Nagoya City are reduced in all cases and the size of the change is almost the same for each price level regardless of the cordon size. Average speed and time lost in traffic jams are also improved in all cases, although these effects within the city center are much better in the Case_1 series than in the Case_2 series. As a result of these changes, CO_2 emissions are greatly reduced after the introduction of a road pricing policy. Changes in the road network flow are shown in Figure 9. We can see that the road traffic flows within the cordon are reduced by about 20% while the flows of links along the cordon and on expressways are increased as traffic is diverted. If the area surrounded by the cordon is small, as in Case_1_700, this reduction covers the whole area.

While a road pricing policy may benefit the environment, such a policy may be very difficult to implement because, among other reasons, stakeholders would object to the sharply fewer trips to the area controlled by the road pricing policy, as noted above. This commonly reported phenomenon of road pricing policy is also seen in this study. Further research is needed on other pricing systems, such as area-based pricing and distance-based pricing, as well as on the inequity issue.

At the same time, a more elaborate model for evaluating road pricing policy is needed. Although the developed model described incorporates some traveler behaviors as an evaluation tools for case studies, this
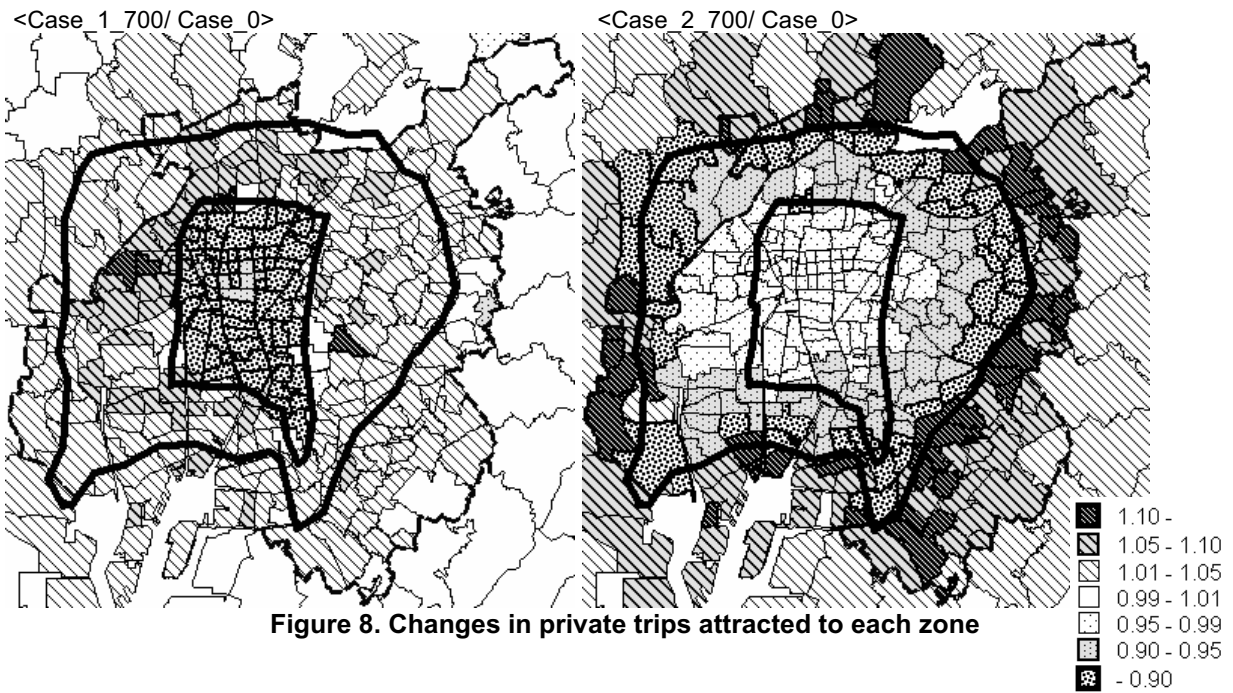
<Case_1_700/ Case_0>   <Case_2_700/ Case_0>

Figure 8. Changes in private trips attracted to each zone

1.10 -
1.05 - 1.10
1.01 - 1.05
0.99 - 1.01
0.95 - 0.99
0.90 - 0.95
- 0.90

Table 5. Effect on road traffic and environmental situation

	Vehicle-Kilometers	Average Speed		Loss Time inTraffic Jam		CO_2 emissions	
	Nagoya city	Nagoya city	City Center	Nagoya city	City Center	Nagoya city	City Center
Case_1_700	-7.6%	+0.39	+0.86	-88.1	-20.3	-4.5%	-16.1%
Case_1_1500	-13.1%	+0.67	+1.49	-54.2	-24.3	-9.9%	-32.8%
Case_2_700	-7.3%	+0.26	+0.01	-88.7	-2.8	-2.5%	-3.1%
Case_2_1500	-12.8%	+0.53	+0.24	-100.7	-4.7	-5.7%	-5.3%

Note: change ratios from Case_0 in vehicle-kilometers and CO_2 emissions;
changes from Case_0 in average speed (unit: km/h) and time lost to traffic jams (unit: h) .
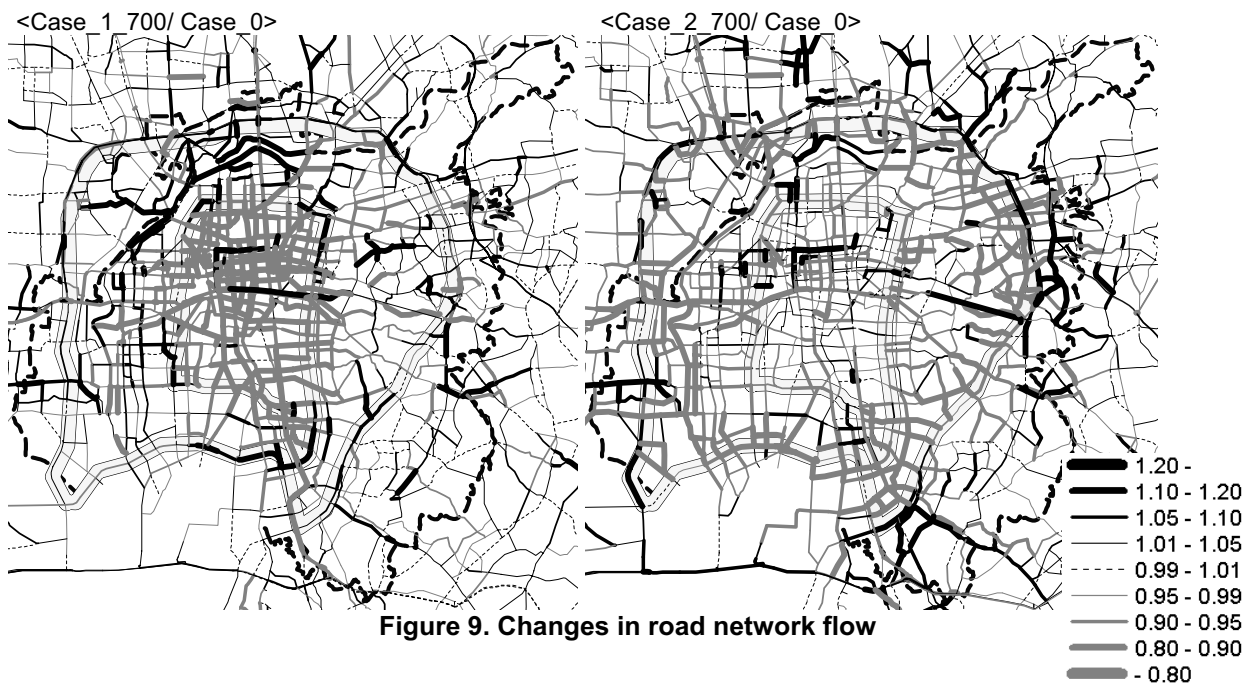
<Case_1_700/ Case_0>   <Case_2_700/ Case_0>

Figure 9. Changes in road network flow

1.20 -
1.10 - 1.20
1.05 - 1.10
1.01 - 1.05
0.99 - 1.01
0.95 - 0.99
0.90 - 0.95
0.80 - 0.90
- 0.80

model ignores the choice of departure time. This results in an overestimation of the number of visitors to the area controlled by the road pricing policy. Furthermore, the model may underestimate the number of visitors because it calculates a different work-place/study-place in each case. Evaluations of the short-term effect of a road pricing policy are more realistic if the workplace is fixed beforehand. However, this may be difficult to do because several million people are involved.

5. Conclusion

In this study, we developed a Semi-Dynamic Combined Stochastic User Equilibrium Model that overcomes or reduces the drawbacks of conventional traffic flow models. The developed model features the following characteristics: 1) It includes traveler activity choices and integrates trip generation (activity choice), destination choice, mode choice and route choice, allowing induced traffic to be measured; 2) It assumes that traveler's choice behavior is expressed as a nested logit structure based on random utility maximization theory; 3) It considers hourly variations in travel times resulting from changes in traffic congestion and the frequency of public transit services, and includes explicit calculation of the time lost in traffic jams; 4) Trip chains along the time axis are approximately modeled; 5) It uses a mathematical optimization approach.

In order to validate the developed model, it was applied to the large-scale transportation network of the Nagoya Metropolitan Area. The results demonstrate the potential of the developed model to effectively compare various policies and evaluate in detail the effects of comprehensive urban transport planning. However, the modeling needs further refinement.

An evaluation of cordon-based road pricing policy confirmed that the environment is effectively improved as a result of the considerably reduced number of car trips that are taken. The improvement is even greater if the area surrounded by the cordoned area is small and the price is higher. On the other hand, the policy also decreases the number of visitors to the area since there is little transfer of trips from car to railway and users tend to change their destination. It may be difficult for stakeholders to agree to the introduction of such a pricing policy because of this reduction in the number of visitors. Therefore, further studies are needed on alternative road pricing systems, such as area-based pricing and distance-based pricing, as well as on the inequity issue. Detailed analysis of comprehensive urban transport plans also is needed.

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