EVALUATION OF ROAD PRICING POLICY WITH SEMI-DYNAMIC COMBINED STOCHASTIC USER EQUILIBRIUM MODEL

Ryo KANAMORI
Ph.D. Candidate, Graduate School of Environmental Studies, Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
Tel: +81-52-789-3730, Fax: +81-52-789-5728
E-mail: kanamori@trans.civil.nagoya-u.ac.jp

Tomio MIWA
Research Associate, Department of Civil Engineering, Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
Tel: +81-52-789-3565, Fax: +81-52-789-5728
E-mail: miwa@civil.nagoya-u.ac.jp

Takayuki MORIKAWA
Professor, Graduate School of Environmental Studies, Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
Tel: +81-52-789-3564, Fax: +81-52-789-5728
E-mail: morikawa@nagoya-u.jp

ABSTRACT

This study analyzes the effect of road pricing using a model with the following characteristics: 1) integration of trip generation (i.e. activity choice), destination choice, mode choice and route choice; 2) consideration of hourly traffic condition variations including queue evolution; and 3) approximate reproduction of trip chain along the time axis. An evaluation of road pricing in the Nagoya Metropolitan Area shows that pricing leads to an effective improvement in the environment as a result of a reduced number of car trips, and at the same time, there is a great reduction in the number of visitors because there is a change of destination and only a small shift to railway.

INTRODUCTION

Nagoya City has come to suffer from chronic traffic congestion and air pollution as a result of overdependence on the automobile. Planning and implementation of improvements to the road and railway networks as well as efforts at transportation demand management (TDM) have aimed at achieving more appropriate automobile usage. Recently, a lot of attention has focused on road pricing, which is one policy for TDM, because of the reported great success of examples in Singapore and London. Since road pricing is a policy by which road users are expected to pay charges, it is supposed that travelers including road users would change their choice of route, mode, destination, departure time and even the decision of whether to travel or not with the introduction of charges. With such changes in traveler behavior, conditions on the road network would also change. Therefore, in order to evaluate road pricing, a model is desired that can calculate the equilibrium state of traffic demand and supply in the transportation network.

Many studies have evaluated road pricing using the equilibrium model in real 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 an elastic assignment model is adopted. Maruyama and Sumalee (3) also use an elastic demand model, even though they compare cordon-based and area-based road pricing using an innovative trip-chain equilibrium model. On the other hand, Maruyama *et al*. (4) analyze the effect 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. Further, de Palma *et al*. (5) take account of departure time, mode choice and route choice in their dynamic equilibrium simulator. Gentile *et al*. (6) utilize multi-class assignment in a multimodal network including trip generation, modal split and route assignment. Although some of these studies express traveler behavior, there has been no study that includes destination choice. Yet, as noted above, road pricing may yield a change in destination as well as route choice. In this work, we improve the evaluation model by introducing destination choice.

The objective of the 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 work is characterized as follows. First, the model considers traveler activity choices (by integrating trip generation, destination choice, mode choice and route choice). Thus it is able to measure induced traffic associated with 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 makes allowances 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, intra-zonal O-D trips and walking trips. The model is formulated using a mathematical optimization approach. As a result, it can be shown that there is unique solution and that this solution 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.

MODEL FORMULATION

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 first outlined briefly. This model is based on a number of assumptions. First, the time period T (in this study, T is set at 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 as equation (1) and the travel time on a link as equation (2).

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

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 possible capacity of link a.

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

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 B.P.R. 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 remnants of flows are given as constants. In addition, x_a^{T*} at the equilibrium state is calculated by a normal solution algorithm (the Frank-Wolf method) substituting $t_a(\cdot)$ as calculated with the usual link performance function by t_a^T given by equation (2). Then the value of X_a^{T*} calculated using equation (1) is treated as the remnant flow on link a in the next time period if it is non-zero.

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.

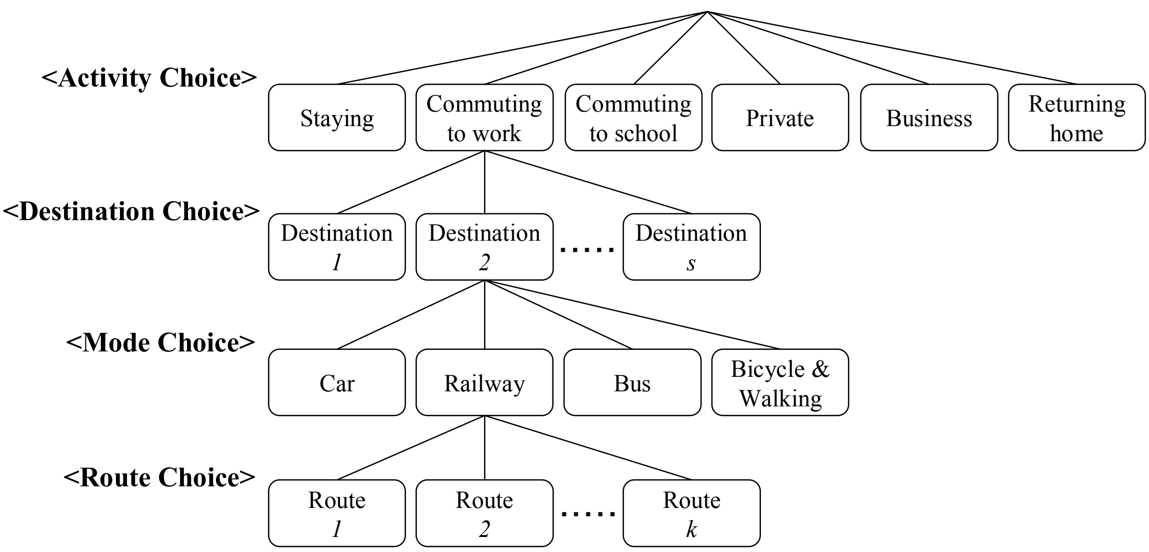


Figure 1. Structure of the Traveler Choice Process in Each Time Period

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 in 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 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. This model is one example of a multi-class user equilibrium model. Since each time-dependent traffic state is achieved independently of other time periods on condition that flow remnants and the number of people present at each location in each zone are given constants, complexity of expression is avoided by omitting the subscript representing a specific time period (T) in the following.

$$\begin{aligned}
\min.\, Z = & \sum_a \int_0^{x_a} t_a(\omega)d\omega + \sum_a \left\{ \max.(X_a^{T-1} + x_a - \mu_a, 0) \right\}^2 \big/ (2\mu_a) + \sum_{i,a} x_a^i \, p_a \big/ \tau^i \\
& + \sum_{i,rs,m,k} \frac{1}{\theta_1^{i,m}} f_{m,k}^{i,rs} \ln(f_{m,k}^{i,rs} \big/ q_m^{i,rs}) + \sum_{i,rs,m',k} f_{m',k}^{i,rs} \, C_{m',k}^{i,rs} \\
& + \sum_{i,rs,m} \frac{1}{\theta_2^i} q_m^{i,rs} \ln(q_m^{i,rs} \big/ Q_{rs}^i) + \sum_{i,rs,m} q_m^{i,rs} \, V_m^{i,rs} \\
& + \sum_{i,rs} \frac{1}{\theta_3^i} Q_{rs}^i \ln(Q_{rs}^i \big/ O_r^i) + \sum_{i,rs} Q_{rs}^i \, V_s^i \\
& + \sum_r \frac{1}{\theta_4^l} [O_{r,l}^0 \ln(O_{r,l}^0 \big/ N_{r,l}) + \sum_i O_r^i \ln(O_{r,l}^i \big/ N_{r,l})] + \sum_{i,r,l} O_{r,l}^i \, V_{r,l}^i
\end{aligned} \tag{3a}$$

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

$$\sum_i x_a^i = x_a, \quad \forall a \tag{3c}$$

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

$$\sum_m q_m^{i,rs} = Q_{rs}^i, \quad \forall i, rs \text{ s} \tag{3e}$$

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

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

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

$$f_{m,k}^{i,rs} \ge 0, \ \ q_m^{i,rs} \ge 0, \ \ Q_{rs}^i \ge 0, \ \ O_r^i \ge 0, \ \ O_{r,l}^i \ge 0, \ \ O_{r,l}^0 \ge 0 \tag{3i}$$

where $f_{m,k}^{i,rs}$: path flow by each mode for each activity; $q_m^{i,rs}$: O-D trips by each mode for each activity; Q_{rs}^i: O-D trips for each activity; O_r^i: generated trips for each activity; $O_{r,l}^i$: generated trips for each activity in each location; $O_{r,l}^0$: the number of people staying at the same location; $N_{r,l}$: the number of people who stayed at the same zone or made a trip in the previous time period; $\delta_{a,k}^{i,rs}$: 1 if link is on k th path between an O-D pair by each mode and 0 otherwise; p_a: price or charge on link; τ^i: the value of time for each activity; $C_{m,k}^{i,rs}$: 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 $V_{r,l}^i$: systematic components of each choice; and $\theta_1^{i,m}$, θ_2^i, θ_3^i and θ_4^l: 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.

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

$$q_m^{i,rs} = \frac{\exp[-\theta_2^i (V_m^{i,rs} + S_m^{i,rs})]}{\sum_m \exp[-\theta_2^i (V_m^{i,rs} + S_m^{i,rs})]} Q_{rs}^i, \qquad S_m^{i,rs} = -\frac{1}{\theta_1^{i,m}} \ln \sum_k \exp[-\theta_1^{i,m} C_{k,m}^{i,rs}] \tag{4b}$$

$$Q_{rs}^i = \frac{\exp[-\theta_3^i (V_s^i + S_{rs}^i)]}{\sum_s \exp[-\theta_3^i (V_s^i + S_{rs}^i)]} O_r^i, \qquad S_{rs}^i = -\frac{1}{\theta_2^i} \ln \sum_m \exp[-\theta_2^i (V_m^{i,rs} + S_m^{i,rs})] \tag{4c}$$

$$O_{r,l}^i = \frac{\exp[-\theta_4^l (V_{r,l}^i + S_r^i)]}{1 + \sum_i \exp[-\theta_4^l (V_{r,l}^i + S_r^i)]} N_{r,l}, \qquad S_r^i = -\frac{1}{\theta_3^i} \ln \sum_s \exp[-\theta_3^i (V_s^i + S_{rs}^i)] \tag{4d}$$

where $S_m^{i,rs}$, S_{rs}^i, S_r^i: the inclusive value.

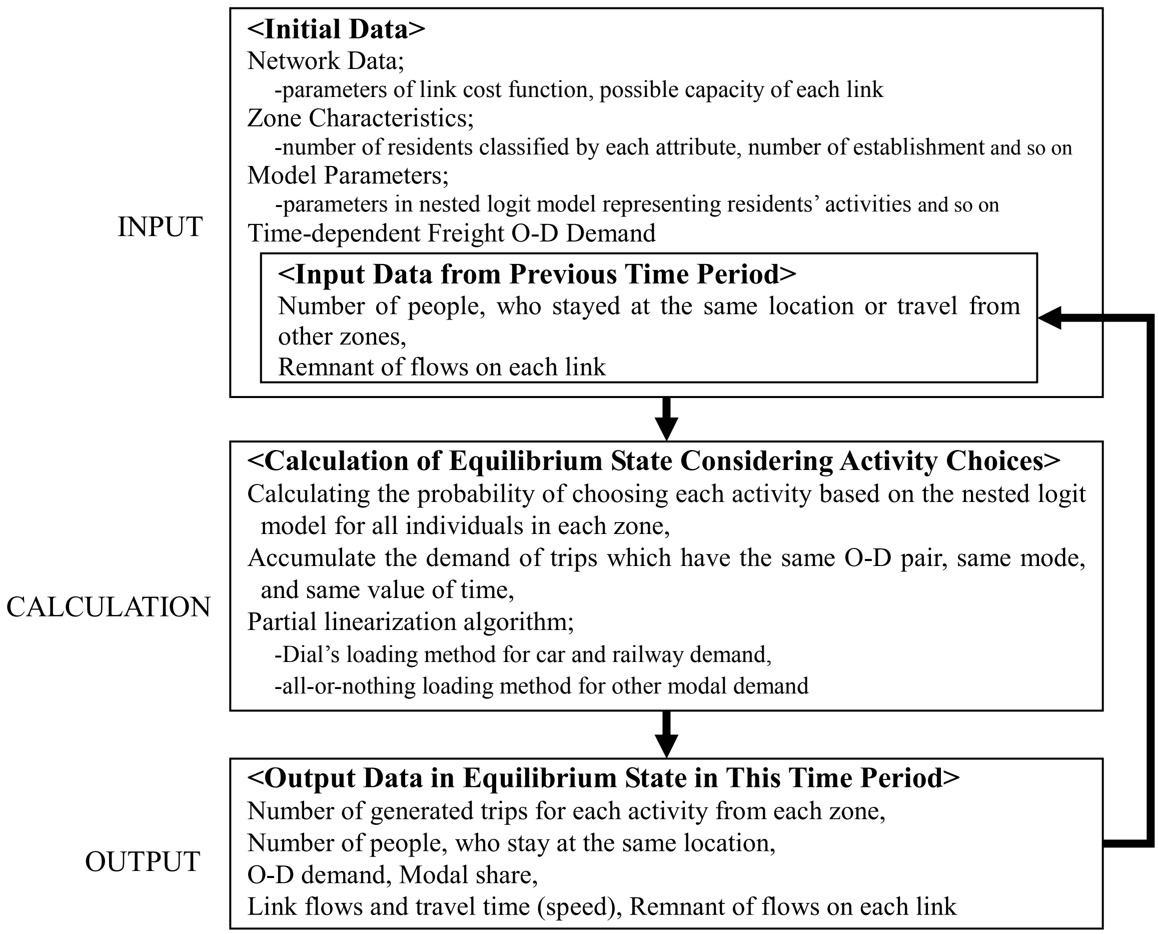


Figure 2. Calculation Procedure for Achieving Equilibrium States in Each Time Period

The partial linearization algorithm (8) can be used to solve this problem efficiently. 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 the zone characteristics. Note that in the first time period only residents 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 equilibrium states in each time period.

APPLICATION TO NAGOYA METROPOLITAN AREA

INPUT DATA AND GIVEN PARAMETERS

In order to apply the developed model to an actual situation, in this case the Nagoya Metropolitan Area, model parameters have to be estimated. Traveler behavior in the area was reported in 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.

It is assumed here that traffic conditions reported by the PT survey 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 (10). The average travel time in each hour by railway and bus is naturally 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 about 1.25km^2. Data representing zone characteristics (such as area, population and others) are obtained using Geographical Information Systems. We also deal with intra-zonal O-D trips whose level-of-service is set to zero for car and bicycle & 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. For drivers, the value of time is set 83.4 JPY per minute for the activities of commuting to work, commuting to school and business. 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 driver's route choice is calculated based on the link weight value of Dial's algorithm (11).

ESTIMATION OF MODEL PARAMETERS

Route Choice and Mode Choice

First, we estimate the parameters of route choice and mode choice for each activity. The route choice model considers only car and railway because of the work involved in developing the alternative route data. Parameters of the route choice model are shared for 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 time spent actually on board trains is 22.1 JPY per minute while other travel time is cost at 36.5 JPY per minute. Intuitively, these values seem appropriate. The calculated value of time spent on board buses is 10.2 JPY per minute while other travel time has a value of 6.3 JPY per minute. Intuitively, these values seem low. This may be due to the flat fare system used on urban transport in Nagoya. In mode choice for private and business trips, the influence of the pre-trip mode, which is the same as that in the previous trip, is taken into consideration. Similarly, a dummy, which is given a value of 1 if the mode chosen is the same as the mode use on the outward trip, is introduced in the mode choice for returning home.

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 excepted because the destination is fixed (the home zone). The parameters are estimated from a choice set of 20 alternatives sampled randomly, since the true number of alternatives is huge (about 300).

Some zone characteristics are adopted as explanatory variables. A ‘Same zone dummy’ is introduced for intra-zonal O-D trips. Every parameter has the expected sign and is statistically significant. Since 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 distance between O-D pairs in addition to inclusive value is estimated negatively, it is described that chosen destinations tend to be nearby places.

Activity Choice

Finally, we estimate the parameters of the activity choice model in each location (Home, Workplace/Study place, Other). Here, since home-to-work and home-to-school trips are daily habitual 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 at zero.

Socio-economic characteristics and current activity duration are adopted as explanatory variables. Every parameter has the expected sign 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 (12, 13) are expressed by the dummy variables according to the specific time period.

MODEL VALIDATION

The model set up with the parameters estimated in the previous section is applied to the Nagoya Metropolitan Area. The road network consists of 22,466 links and 7,606 nodes. We use a B.P.R. type link performance function whose parameters were estimated recently in Japan (14, 15). Since freight data is not included in the PT survey, they are set 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 (14).

In this particular study, in order to verify that traffic states throughout the period 3 a.m. to midday which includes the morning peak time period, the number of residents in each zone is set at 3:00 a.m. The total numbers of trips generated in each time period is well replicated along the time axis, although there is a systematic underestimation after 9 a.m. One reasonable explanation of this tendency to underestimate is that we assume that travelers do not make more than one trip in each time period. The total number of trips attracted to Nagoya city is estimated as 80% of the PT survey data because of this underestimation of trip generation. The reproducibility of modal share, however, is roughly correct. The ability to accurately predict destination choice in Nagoya is high. Further, with a correlation coefficient of 0.76 and a regression coefficient of 0.82, the reproducibility of car link flow is relatively good. Given these results, it can be said that the developed model is largely validated and that it will be useful for large-scale transportation planning, even though the total number of trips tends to be underestimated somewhat.

EVALUATION OF ROAD PRICING POLICY

The effect of cordon road pricing policy is analyzed using the developed model. Here, cordon road pricing is a system by which road users entering a cordoned area have to pay a charge. In order to compare the effect of varying cordon areas and price levels, the following cases of charging are introduced, with charges beginning at 7 a.m.

- ***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; 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 3. The inner line encloses the city center while the outer line corresponds to most of Nagoya City. The price is converted into travel time by the value of time for each activity.

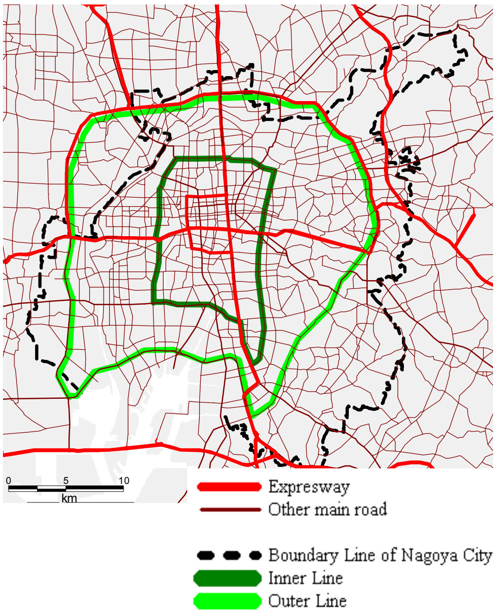
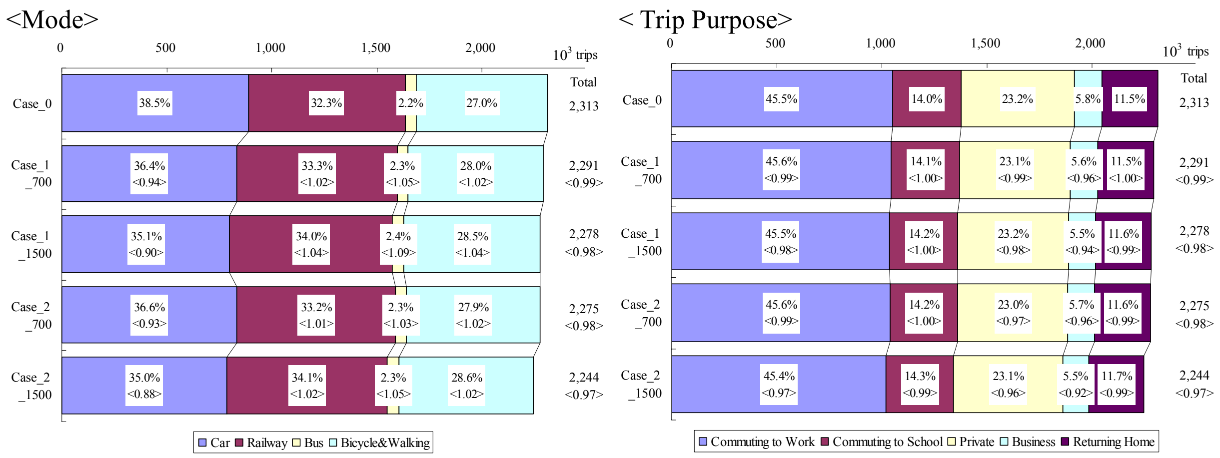


Figure 3. Cordon Lines in Case Studies

Figure 4 shows the comparison of the number of trips attracted to Nagoya City. For every case with pricing, there is little change in the total number of trips from Case_0 (with no pricing), although the number of car trips is reduced 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 5 compares the number of trips in 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, as compared with the Case_2 series. In particular, Case_1_1500 leads to 55% fewer car trips. It turns out that the shift from car to railway within the city center, where the railway network is sufficiently developed, is smaller than we expected and the number of private and business trips is reduced sharply. According to Table 1, in which the changes in O-D trips are shown, 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 decreased, even though railway trips from within Nagoya City to the city center increase (in Case_1_700: 7%; in Case_1_1500: 12%).



Note: figures in angle brackets denote the rate of change from case_0.

Figure 4. Number of trips attracted to Nagoya City

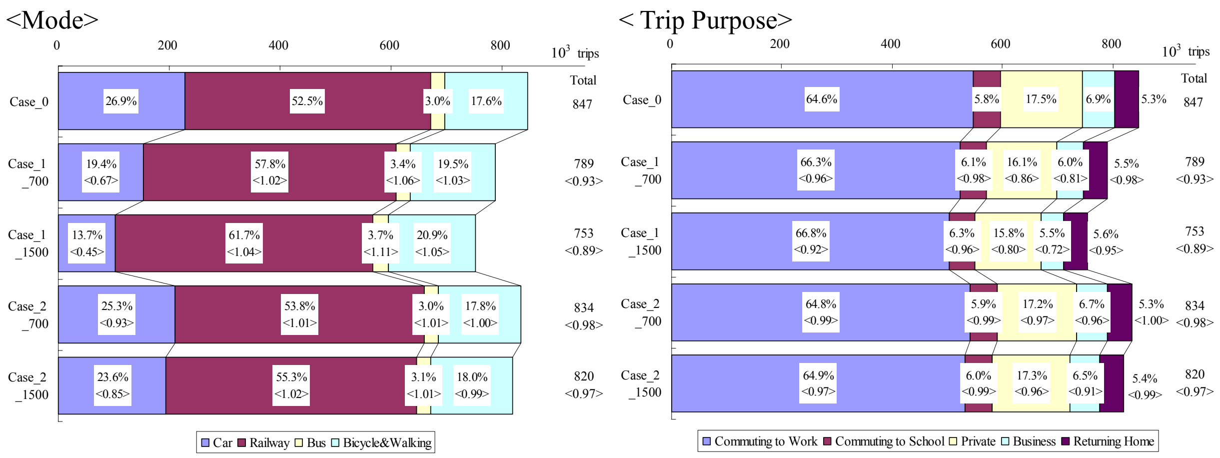


Figure 5. Number of trips attracted to the City Center

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

Table 1. Changes in O-D trips

It is supposed that decisions to change destination or not to travel at all arise frequently. (That is, the shift from car to railway caused by road pricing is small.) Changes of in private trips attracted to each zone are shown in Figure 6 as one example. It is clear that the main choices of alternative destinations are in the fringe areas; trips in zones adjacent to the cordon increase. In addition, the larger the area surrounded by the cordon, the larger the number of zones influenced by this behavior. This result suggests that, in order to increase the number of visitors to the city center, other policies (such as railway fare discounting) should be implemented in conjunction with road pricing.

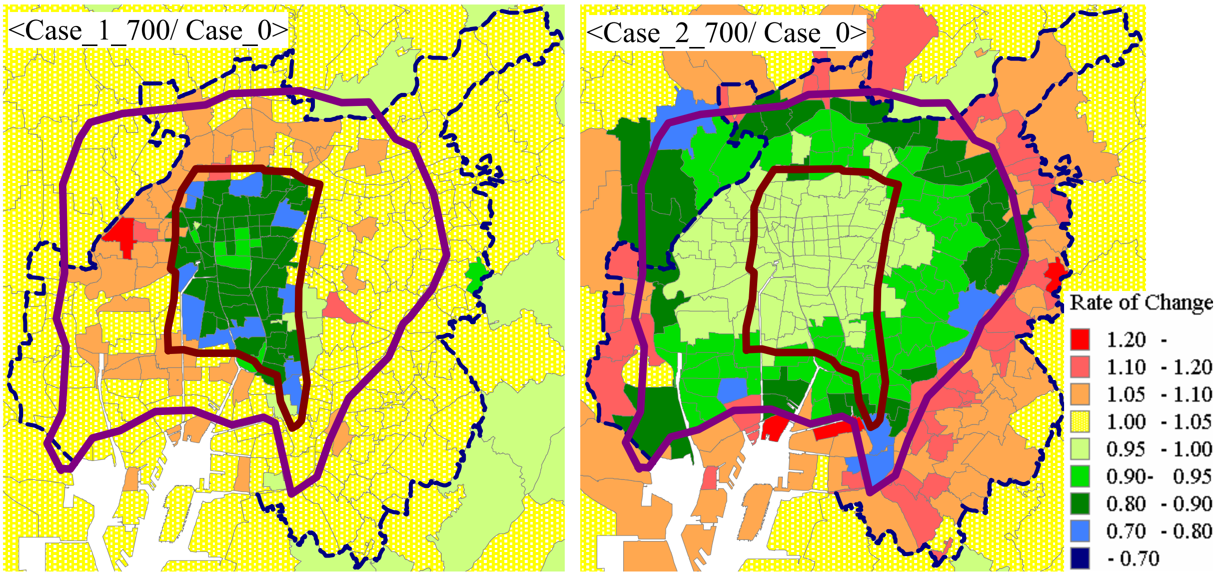


Figure 6. Changes in Private Trips Attracted to Each Zone

	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).

Table 2. Effect on Road Traffic and Environmental Situation

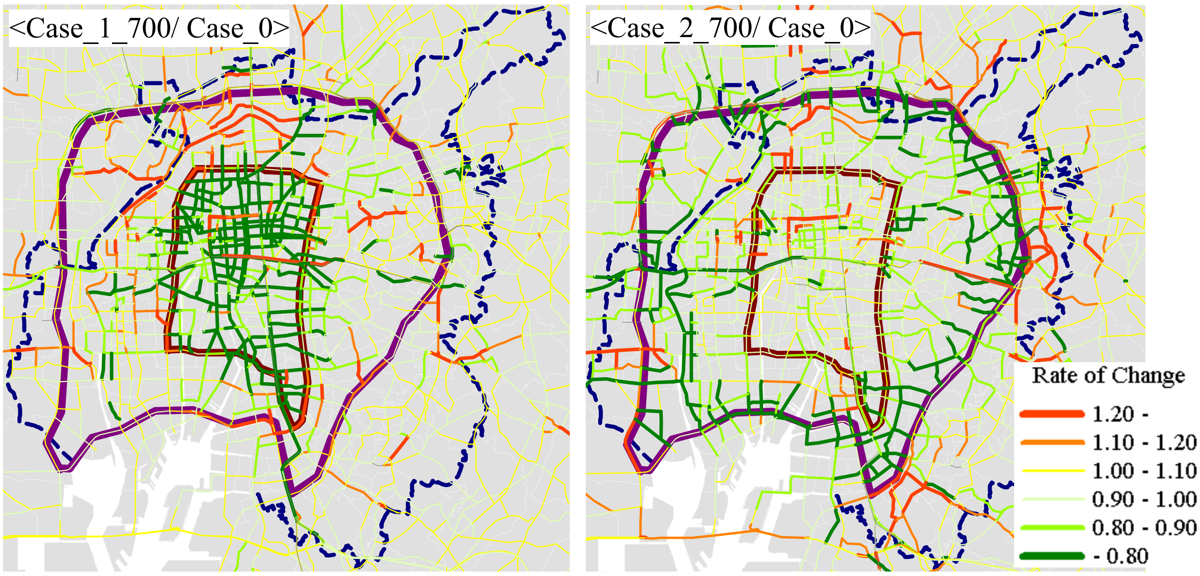


Figure 7. Changes in road network flow

Table 2 shows the effect on road traffic and the environmental situation. 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 in the Case_1 series are much better 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 road network flow are shown in Figure 7. We can see that road traffic flows within the cordon are reduced by about 20% while along the cordon and on expressways they are increased as traffic is diverted. If the area surrounded by the cordon is small, as in Case_1_700, this reduction in traffic covers the whole area.

From an environmental viewpoint, road pricing may be a desirable policy. However, it may be very difficult to judge and implement. The reason is that, for example, agreement with shop owners would be hard to reach because the number of trips attracted to the priced area decreases sharply as analyzed above. This phenomenon is a commonly reported result of implementing road pricing and is also made clear in this study. Further research on another pricing system, such as area-based pricing and distance-based pricing, and the inequity issue will be needed.

CONCLUSION

In this study, we have 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) includes traveler activity choices; integrates trip generation (activity choice), destination choice, mode choice and route choice allowing induced traffic to be measured; 2) traveler choice behavior assumed to be expressed as a nested logit structure based on random utility maximization theory; 3) considers hourly variations in travel time resulting from changes in traffic congestion and frequency of public transit services and also includes explicit calculation of time lost in traffic jams; 4) trip chains along the time axis are approximately modeled; 5) mathematical optimization approach used in formulation.

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

Through an evaluation of cordon-based road pricing, it is confirmed that the environmental situation is effectively improved as a result of the considerable reduction in car trip numbers. If the area surrounded by the cordon is small and the price higher, the improvement in the priced area is better. On the other hand, it turns out that the policy also brings a decrease in visitors to the priced area since there is little transfer of trips from car to railway and users tend to change their destination. It may be difficult for shop owners to agree with the introduction of such a pricing policy because of this reduction in the number of visitors. Therefore, further studies on alternative road pricing systems, such as area-based pricing and distance-based pricing, as well as the inequity issue are needed. Detailed analysis of comprehensive urban transport plans will be needed.

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