On the Effects of Central Japan Expressway's Commuter Toll Discount Policy in Nagoya Area

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Abstract: Road pricing policies have two equally important objectives that have to be considered: the optimal use of the road network and the fiscal sustainability for the management of the network. The aim of this work is to examine the effects on these two objectives of a recent pricing policy implemented in Japan's expressway networks. Recently the Nippon (Japan) Expressway Companies (NEXCO, operators of Japan's nation wide expressway network) have implemented several toll discount policies for users equipped with electronic toll collectors (ETCs). One of the policies is the commuter discount policy that discounts 50% for a journey on the NEXCO expressway no longer than 100 km during the commuting peak hours. This paper examines its effect on congestion reduction in the road network of Nagoya area and its influence on the use of expressways operated by another major local public expressway company in Nagoya. The congestion easing effect of this policy is compared with a potential marginal cost pricing scheme. These observations suggest that policy coordination regarding toll levels is needed for expressway corporations and transportation authorities for improving transportation efficiency of utilization of the whole network.

Key words: electronic toll collector (ETC); expressway toll; discount; user equilibrium; marginal cost pricing; revenue

Introduction

Congestion road pricing has long been advocated as an efficient and theoretically sound measure for easing traffic jams. Nevertheless, only very few cities in the world have implemented congestion road pricing policies. Although the advance of electronic and communication technology has already overcome most technical difficulties, there still remains high hurdles in social agreement for accepting congestion tolls. In contrast, it may be easy to design and carry out efficient pricing policies on existing toll roads for adjusting traffic flows to ease congestion.

In Japan, while congestion pricing has not been introduced on urban roads, all expressways are tolled. The nation wide expressways are operated by the East, Central, and West Nippon (Japan) Expressway Companies (NEXCO, privatized from the former Japan Highway Public Corporation since October 2005). NEXCO has recently implemented several kinds of toll policies which are relevant to efficient use of expressways and reduction of traffic in parallel urban roads. A typical policy is the commuter discount policy that discounts 50% for a journey on the NEXCO expressway no longer than 100 km during the commuting peak hours, for vehicles equipped with electronic toll collectors (ETCs). This policy has been put into effect since January 2005, in the NEXCO expressway network except Tokyo and Osaka areas.

NEXCO's discount schemes arose from the pressure

that Japan's expressway tolls are considered to be higher than the proper level. Japan's expressways have been constructed based on the cost repayment principle, which requires that the toll revenues collected should be equal to the total cost, including capital cost and operational cost. In part of the NEXCO expressway network in less industrialized regions of Japan, traffic volumes are small and toll revenues can hardly serve the debt born of the investment for expressway construction. However, mostly in industrial regions, NEXCO's toll revenues are indeed bigger than costs. There is a strong public opinion that requires lowering expressway tolls.

In the meanwhile this discount scheme is also expected to have the effect of relieving traffic congestion in particular in the parallel urban roads during the peak hours by absorbing more traffic onto expressways. In this sense, the expressway toll discount policy has a similar effect as peak road congestion pricing imposed on streets, assuming that the capacities of expressways are not fully utilized. This assumption is true in parts of NEXCO's expressway network. It does not hold in Tokyo and Osaka, the most densely inhabited areas of Japan. This is one of the reasons that the commuter discount policy does not apply to Tokyo and Osaka. (In Tokyo and Osaka, another toll discount policy is enforced which gives discounts to drivers from midnight until the morning peak time.)

Among the urban areas where the peak hour commuter discount policy is applied, Nagoya is the biggest and suffers from heavy road congestion. The study of Nagoya's case may then reveal the most important impact of NEXCO's commuter discount policy. Based on a network equilibrium analysis approach (see Refs. [1-5]), this paper examines the effect of NEXCO's commuter discount policy on congestion reduction in the road network of the Nagoya area. The effect of the policy is compared with that of the potential marginal cost pricing scheme.

In the urban district of Nagoya, there are several expressways operated by another urban expressway corporation — the Nagoya Expressway Public Corporation (NE). NEXCO's unilateral discount policy unfortunately has a negative side effect that reduces the use of NE's expressways, which may cause inefficiency in utilizing road resources in the whole network. Furthermore, this discount policy may also reduce the toll revenue of NE and thus bring about financial difficulties to NE, which will also be examined in this paper.

1 User Equilibrium Analysis Model

NEXCO's commuter discount applies to vehicles satisfying the following conditions. (See http://www. nexco. ne.jp/commutation_discount.)

(1) Equipped with ETC;

(2) Enter or exit from NEXCO expressways during the peak periods 6 am-9 am and 5 pm-8 pm;

(3) The journey on the NEXCO network should be no longer than 100 km; and

(4) The first use of NEXCO expressways in the peak period.

For instance, the total toll for a journey shown in Fig. 1 is $\frac{1}{2}T_1 + T_2$. If the second expressway segment's length is also less than 100 km and a vehicle enters into it without passing the first, then the toll for the vehicle will be $\frac{1}{2}T_2$. Thus, the tolls are path sensitive.
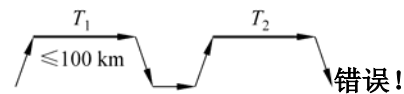

Fig. 1 Two expressway segments with tolls T_1 and T_2

In this paper a user equilibrium analysis method for traffic network with this kind of cost structure will be provided to evaluate the impact of the discount policy. Equilibrium models have long been applied in transportation network planning and management[1,2]. Conventional equilibrium models usually deal with networks in which path costs can be expressed as sums of link costs which are identical for all paths. Most recently, traffic equilibrium problems with path-specific cost structures have been addressed[3-5] and efficient computational algorithms have been designed for particular classes of networks[5]. The equilibrium model and solution method described in the following can be regarded as a new class of such kind of equilibrium analysis methods.

1.1 Network model

The notations for describing the traffic network are as follows.

A: set of links;

$m = 1,...,M$: indices of vehicle types;

$v_{m,a}$: link flow of type m vehicle in link a;

ρ_m : passenger car unit (pcu) coefficient for vehicle of type m;

v_a, $a \in A$: link flow in pcu, $v_a = \sum_m \rho_m v_{m,a}$, $\boldsymbol{v} = \{v_a, \ a \in A\}$ is the link flow vector;

$t_a(v_a)$, $a \in A$: link travel time, increasing function in v_a, $\boldsymbol{t} = \{t_a(v_a), \ a \in A\}$;

$W = \{rs\}$: set of origin destination (OD) pairs;

R_{rs}, $rs \in W$: set of routes from r to s;

$\delta_{k,a}^{rs}$: $\delta_{k,a}^{rs} = 1$ if k contains a, $\delta_{k,a}^{rs} = 0$ otherwise;

q_m^{rs}, $rs \in W$: travel demand for OD rs;

$f_{m,k}^{rs}$, $k \in R_{rs}$: path flow of type m vehicle in path k from r to s, $\boldsymbol{f} = \{f_{m,k}^{rs}, k \in R_{rs}, 1 \leqslant m \leqslant M\}$ is the vector of path flows, $v_{m,a} = \sum_{rs,k} f_{m,k}^{rs} \delta_{k,a}^{rs}$;

$T_{m,k}^{rs}$: toll for type m vehicle using path k;

β_m : value of time for type m vehicle;

$C_{m,k}^{rs} = \sum_a t_a \delta_{k,a}^{rs} + \dfrac{1}{\beta_m} T_{m,k}^{rs}$: generalized travel cost in path k for type m vehicle;

$u_m^{rs} = \min_k \left\{ C_{m,k}^{rs} = \sum_{a \in A} t_a \delta_{k,a}^{rs} + \dfrac{1}{\beta_m} T_{m,k}^{rs} \right\}$: minimum cost for OD rs for type m vehicle.

The user equilibrium is a state of the network where for each OD rs and vehicle type m, if a path k is used, the minimum cost is u_m^{rs}. The user equilibrium conditions can be formulated as follows.

$$f_{m,k}^{rs} \geqslant 0, \ rs \in W, k \in R_{rs}, 1 \leqslant m \leqslant M,$$

$$\sum_k f_{m,k}^{rs} = q_m^{rs}, rs \in W,$$

$$f_{m,k}^{rs} > 0 \Rightarrow \sum_{a \in A} t_a \delta_{k,a}^{rs} + \frac{1}{\beta_m} T_{m,k}^{rs} - u_m^{rs} = 0,$$

$$rs \in W, k \in R_{rs}, 1 \leqslant m \leqslant M.$$

1.2 Solution method

The above equilibrium conditions can be formulated as the following mathematical programming problem.

$$\min Z(\boldsymbol{f}) = \sum_{a \in A} \int_0^{v_a} t_a(\omega) \mathrm{d}\omega + \sum_m \frac{\rho_m}{\beta_m} \sum_{rs,k} T_{m,k}^{rs} f_{m,k}^{rs},$$

subject to

$$q_m^{rs} - \sum_{k \in R_{rs}} f_{m,k}^{rs} = 0, \ rs \in W, 1 \leqslant m \leqslant M,$$

$$f_{m,k}^{rs} \geqslant 0, \ rs \in W, k \in R_{rs}, 1 \leqslant m \leqslant M,$$

with $v_a = \sum_{rs \in W, k \in R_{rs}} \left(\sum_{1 \leqslant m \leqslant M} \rho_m f_{m,k}^{rs} \right) \delta_{k,a}^{rs}$, $a \in A$. Assume that t_a is a strictly increasing function, and then Z is strictly convex in $\boldsymbol{v} = \{v_a, \ a \in A\}$. Since $\boldsymbol{v}$ is a linear combination of $\boldsymbol{f}$, Z has a unique minimal value at a unique solution $\boldsymbol{v}$, over the convex set of domain for $\boldsymbol{f}$. The minimization problem is a typical convex programming problem and can be resolved by the Frank-Wolfe method[6]. For the problem under investigation, the link flow vector $\boldsymbol{v}$ should be computed. The Frank-Wolfe method can be implemented by the following procedure which computes equilibrium link flow vector $\boldsymbol{v}$.

Let $S = \sum_m \dfrac{\rho_m}{\beta_m} \sum_{rs,k} T_{m,k}^{rs} f_{m,k}^{rs}$.

Step 1   Set initial values for $\boldsymbol{v}^0 = \{v_a^0 = \sum_m \rho_m \sum_{rs,k} f_{m,k}^{rs,0} \delta_{k,a}^{rs}\}$ and $S^0 = \sum_{rs,k,m} T_{m,k}^{rs} f_{m,k}^{rs,0}$, $n = 0$;

Step 2   Compute $\boldsymbol{t}^n = \{t_a(v_a^n), a \in A\}$. For $rs \in W$, for each m, find a minimum cost route k for type m vehicle. For this route k, set $f_{m,k}^{rs} = q_m^{rs}$. Compute link flows $\boldsymbol{v} = \left\{ \sum_{rs \in W} \left(\sum_{1 \leqslant m \leqslant M} \rho_m f_{m,k}^{rs} \right) \delta_{k,a}^{rs}, a \in A \right\}$ by all-or-nothing assignment. Compute the term $S = \sum_m \dfrac{\rho_m}{\beta_m} \sum_{rs} T_{m,k}^{rs} f_{m,k}^{rs}$ in the assignment process.

Step 3   Compute the minimum point α for $Z(\alpha) = \sum_{a \in A} \int_0^{\alpha v_a + (1-\alpha)v_a^n} t_a(\omega) \mathrm{d}\omega + \alpha S + (1-\alpha)S^n$;

Step 4   Set $\boldsymbol{v}^{n+1} = \alpha \boldsymbol{v} + (1-\alpha)\boldsymbol{v}^n$, $S^{n+1} = \alpha S + (1-\alpha)S^n$. If $|v_a^{n+1} - v_a^n| < \varepsilon$, $\forall a \in A$, for some given error bound, stop; otherwise, set $n = n+1$, return to Step 2.

In Step 2, the assigned link flow vector $\boldsymbol{v}$ and the term S depend on path flows $\{f_{m,k}^{rs}\}$. Since only one minimum cost path is assigned for each OD pair and each vehicle type, the computation time is proportional to the product of the number of vehicle types, the number of OD pairs and the time for path search. Note that since $\boldsymbol{v}$ and S are additive functions in path flows $\{f_{m,k}^{rs}\}$, the data of each path flow can be eliminated after its contribution to $\boldsymbol{v}$ and S has been counted for. The Frank-Wolfe method can actually be

implemented in a link-based manner, as long as the minimum cost paths can be generated in a link-based manner. The main difficulty encountered here is the search for a minimum cost path for a vehicle which is equipped with ETC and can benefit from the toll discount policy. This problem can be solved by the following method composed of two parts. For an origin r, the method finds minimum cost paths to all the nodes in the network.

Part 1 Exclude NEXCO expressways from the network. For each node j use the Dijkstra algorithm to compute the minimum cost C_{rj}^0 from r.

Part 2 For all j, compute minimum cost C_{rj} recursively in the complete network (including NEXCO expressways) by the following rules. Let $B(j) = \{i; ij \in A\}$. Let t_{ij} be the travel time from i to j, and T_{ij} be the toll for link ij, $i \in B(j)$. Assume that C_{ri} has been computed.

(1) Suppose ij is an entry-exit pair of NEXCO expressway, and the distance between ij is $\leqslant 100$ km. If NEXCO expressway has not been used up to node i, $C_{rj}(i) = C_{ri} + t_{ij} + \frac{1}{2}T_{ij}$. If NEXCO expressway has been used up to node i, then $C_{rj}(i) = \min\left\{C_{ri}^0 + t_{ij} + \frac{1}{2}T_{ij}, C_{ri} + t_{ij} + T_{ij}\right\}$. See Fig. 2 for illustration.

Fig. 2   Illustration for (1)

(2) If ij is a NEXCO link of length > 100 km or is a non-NEXCO link, set $C_{rj}(i) = C_{ri} + t_{ij} + T_{ij}$.

(3) $C_{rj} = \min\left\{C_{rj}(i), i \in B(j)\right\}$. Record the following information for node j: (a) Whether NEXCO expressway has been used or not up to j; (b) The ascending node i.

1.3 Congestion measure

There are many possible measures for evaluating the congestion state of a traffic network. Two typical measures are total travel time and total cost in monetary terms (see Ref. [7]). However, these measures are mainly based on economic considerations and may not be exact for describing the physical congestion state in the roads. An exact measure should be one which takes into account the occupancy of various vehicle types. In the following, we use $\rho_m v_{m,a}$ as an approximate indicator for measuring the occupancy of type m vehicles in a link a. Therefore, we have the following measure for evaluating the state of congestion in the whole network

$$T = \sum_{a \in A} \sum_{m=1}^{M} \rho_m v_{m,a} t_a ,$$

where $\left(\sum_m \rho_m v_{m,a}\right) t_a$ is the modified travel time cost on a link a.

2   Road Network in Nagoya Area

The network to be studied is the road network of the metropolitan area centered at Nagoya. The network has 3458 nodes and 10 911 (directed) links in total. As shown in Fig. 3, the main highway routes in the network are NEXCO's inter-city expressways (abbreviated as IC) and a ring expressway (abbreviated as RING) in Nagoya, and several routes managed by the Nagoya Expressway Public Corporation (owned by Nagoya City, abbreviated as NE). Both the RING and the NE have uniform toll rates, while the IC highway tolls are proportional to distance.

Fig. 3   Highway network in Nagoya Metropolitan Area as of 2006

The data for the network and the travel demand is from "the Fourth Chukyo (Nagoya Area) Personal Trip Survey" undertaken in 2001[8]. In the "the Fourth

Chukyo (Nagoya Area) Personal Trip Survey", the network for the year 2001 and the network planned for the year 2015 are given, the current network was generated by adding to the 2001 year network the links already constructed according to the 2015 year plan.

There are 105 671 OD pairs. Vehicles are classified in four types as shown in Table 1.

Table 1　Vehicle types, their values of time (VOT), and passenger car unit (pcu) coefficients

Type	VOT[*]（Yen/min）	pcu coefficient
Car	62.86	1
Bus	519.74	2
Small truck	56.81	1
Truck	87.44	2

*Note: Data from "Manual for Benefit Analysis", Road Bureau, Ministry of Land, Infrastructure and Transportation, Japan, (August, 2003)

The following BPR functions modified for Japan's roads are used as link cost functions[9].

$$t = t_0 \left(1 + \alpha(v/K)^\beta\right), \ \alpha = 0.48, \ \beta = 2.82,$$

where v is link traffic flow, K is link capacity, and t_0 is free flow link travel time.

The accuracy of our equilibrium model is verified on the network of the year 2001. Daily traffic counts of highways were used as indicators for evaluating the accuracy of the model. Figure 4 plots the flows estimated by the model and those observed. The observed values are the average daily flow in November, 2001[10].
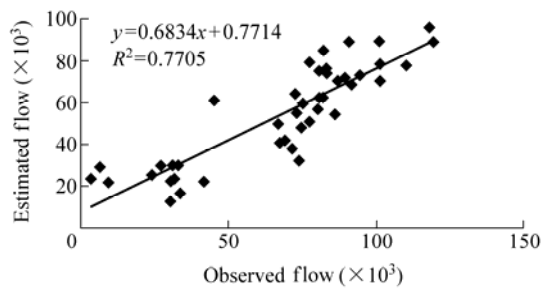

Fig. 4　Comparison of estimated and observed highway flows

The determination coefficient between the two sets of figures is 0.77 (correlation coefficient 0.87), which shows a rather good coincidence of the estimated flows with true flows. We believe that this justifies our use of the user equilibrium model for predicating the effects of toll policies.

3　Effects of the Commuter Discount Policy

As the morning and the afternoon peak periods are temporarily separated and can be treated independently, we will only focus on the impacts of the discount policy in the morning period. The demand in the morning three peak hours is about 23.15% of the daily demand[8]. As the ratio of ETC-equipped vehicles in all the vehicles using expressways is growing rapidly in Japan, and in reality drivers who may potentially be benefited by using the NEXCO discount policy tend to set ETC, in the following, the extreme case that all the vehicles are equipped with ETC will be investigated.

In Table 2, travel cost measured by pcu·hour on free roads, ramps, and expressways for both the cases with and without commuter discount policy are shown. The travel cost on free roads has a slight reduction of −1.72%, but the total cost on the whole network is only slightly reduced due to increases of travel cost on expressways and ramps.

Table 2　Travel cost for cases with and without commuter discount policy

	Travel cost（1000 pcu·hour）			Change (%)
	Without	With	Change	
Free roads	951.5	935.1	−16.4	−1.72
Ramps	11.7	12.3	0.6	5.22
Expressways	419.1	430.4	11.3	2.70
Total	1382.3	1377.8	−4.5	−0.32

Travel costs on free roads of Nagoya city, Nagoya's central area (which is enclosed by the NE inner ring expressway), the rest of the network, for both the cases with and without commuter discount policy are shown in Table 3. Travel cost on free roads of Nagoya and central Nagoya have a relatively large reduction (by 3.01% and 2.58%), compared with the reduction in the rest of free roads.

Table 3　Change of travel cost in free roads within Nagoya

	Travel cost (1000 pcu·hour)			Change (%)
	Without	With	Change	
Nagoya	105.0	101.9	−3.1	−3.01
Central Nagoya	54.9	53.5	−1.4	−2.58
Rest	791.6	779.8	−11.8	−1.49

The change of revenues for the NEXCO and NE expressways are shown in Table 4. The NEXCO expressways have a decrease of toll revenue of 8.12% and the NE expressways have a decrease of 1.59%, which suggests that NEXCO's toll policy change has an influence on NE's revenue though the influence is not so remarkable compared to the influence on its own revenue.

Table 4   Change of traffic volume in expressways in the morning peak hours

	Revenue (Million Yen)		
	Without	With	Change (%)
NEXCO	602.1	553.3	−8.12
NE	42.3	41.6	−1.59

4   Comparison with Marginal Cost Pricing

In order to find out to what degree the NEXCO's commuter discount policy contributes to congestion reduction in the traffic network of the Nagoya area, in the following, we compare the effect of the commuter discount policy with that of marginal cost pricing (MCP) mechanism[7].

The total travel cost in monetary terms is defined as

$$\text{TC} = \sum_a \sum_m \beta_m v_{m,a} t_a, \ t_a = t_a\left(\sum_m \rho_m v_{m,a}\right),$$

and the marginal cost of m-type vehicle in road link a is

$$\text{MCP} = \frac{\partial \text{TC}}{\partial v_{m,a}} = \beta_m t_a + \rho_m\left(\sum_m \beta_m v_{m,a}\right)t_a'.$$

For achieving a state of minimum cost, it suffices to impose on an m-type vehicle a toll $\rho_m\left(\sum_m \beta_m v_{m,a}\right)t_a'$. The user equilibrium problem with this tolling mechanism can be solved by using $t_a + \rho_m\left(\sum_m \beta_m v_{m,a}\right)t_a'\beta_m^{-1}$ as a link cost function. The travel cost changes on various road types with MCP tolling are shown in Table 5. Although there is a relatively big increase of cost on ramps, cost on both the free roads and expressways are reduced, resulting in a reduction of total cost. In contrast, the commuter discount policy has only limited effects on reduction of total travel time.

However, the commuter discount policy does have comparatively larger effect on congestion reduction in some areas. Table 6 shows the travel costs on Nagoya, central Nagoya, and the rest area, with the MCP mechanism. In central Nagoya the commuter discount policy achieves more than half (2.58% as compared to 4.45%) of the effect of MCP tolling. Therefore, NEXCO's discount policy serves as a good alternative measure for congestion pricing for reducing travel cost in the central part of the Nagoya metropolitan area.

The change of flows on the NEXCO and NE expressways under the MCP scheme are shown in Table 7, with a comparison to the current toll discount case. NEXCO highways should accommodate greater flows

Table 5   Change of travel cost with MCP

	Travel cost (1000 pcu hour)			Change (%)	Change with commuter discount (%)
	Regular pricing	With MCP	Change		
Free roads	951.5	904.9	−46.6	−4.90	−1.72
Ramps	11.7	17.5	5.8	49.78	5.22
Expressways	419.1	425.7	6.6	1.58	2.70
Total	1382.3	1348.1	−34.2	−2.47	−0.32

Table 6   Change of travel cost in free roads within Nagoya with MCP

	Travel cost（1000 pcu hour）			Change (%)	Change with commuter discount (%)
	Without	With	Change		
Nagoya	105.0	92.2	−12.8	−12.18	−3.01
Central Nagoya	54.9	52.4	−2.4	−4.45	−2.58
Rest	791.6	760.2	−31.3	−3.96	−1.49

for optimal use of the network. For optimal use, the NE expressways should accommodate about twice the flows, while by the current discount policy, flows on the NE expressways are reduced.

Table 7 Comparison of the discount scheme and the MCP scheme on flows in expressways for 1000 pcu

	Flows in regular case	Discount		MCP	
		Flows	Change (%)	Flows	Change (%)
NEXCO	276.8	327.6	18.35	376.6	36.05
NE	66.1	65.0	−1.66	129.6	96.07

5 Conclusions

In this paper the impact of the Japan Expressways commuter discount policy on traffic congestion relieving in free roads and on management of competing expressways is analyzed based on a user equilibrium model. Although congestion on free roads may be alleviated, the total effect is not significant due to travel cost increase in the NEXCO expressways. NEXCO's toll discount policy reduces the use of the expressways operated by the Nagoya Expressway Corporation, which has a negative effect on the efficiency of the whole network because under the optimal MCP scheme the NE expressways should have an increase of 96% of users. This also reduces NE toll revenue. Because the commuter discount policy is carried out only during the peak periods, the reduction of NE's revenue is limited. However, for efficient use of NE's expressway resources during the peak periods, it is necessary for NE to set a lower toll level. This might further cut its revenue. So, in the future, perhaps an ideal scheme is to simultaneously charge the urban road users and use the revenue to subsidize the expressway corporations.

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