Application of self-selected pricing to the Japanese highway fee system based on the ETC

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Abstract

This study focuses on the ETC commuting discount which is applied to travels of less than 100km except in metropolitan areas. In theory, it is regarded as a self-selecting road pricing which discriminates users on the basis of payment means, travel distance, time period, and space. The purpose of this policy must speed up the spread of ETC use as a mode of collection of highway fees. In order to achieve this, users must be presented with long-term incentives for installing ETC devices in their automobiles. Therefore, it is not always the case that the introduction of a self-selecting fee system benefits users. To comprehend the relations between the ETC commuting discount and variations of highway congestion, this study applies the traditional bottleneck congestion model to the ETC commuting discount of highway fees regarded as self-select road pricing. From the results, it can be inferred that the self-select pricing mechanism eliminates the negative effects of granting discount in the peak period; however, the mechanism may not work when ETC use becomes widespread. The conditions are based on the number of ETC users, the capacity of the bottleneck, and the length of the discounted period.
Keywords: road pricing, self-selecting fee system, bottleneck congestion.

1 Introduction

In recent times, with the introduction of the electric toll collection (ETC) system, several discounts have been given on the Japanese highway fee system. This study focuses on the ETC commuting discount considered as the representative of such discounts in the amount of utilization. This discount is applied to travels of less than 100km except in metropolitan areas. In theory, it is regarded as a self-selecting road pricing, which discriminates between users on the basis of payment means, travel distance, time period and space.

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According to Train [1], when a customer has a choice between two or more fee systems, the fee systems are referred to as 'self-selecting'. Self-selecting fee systems are implemented as the payment system in many public services such as water, gas and telecom. In general, most revisions to an existing fee system adversely affect a portion of the customer base. However, customers can choose not to avail of new fee systems and thereby pre-empt any negative impact. This is because self-selecting fee systems are normally introduced as alternatives to the customer, owing to which he/she can continue with the existing fee system if the new option does not seem viable. Furthermore, if the service agency can find additional fee systems that can increase their profits, the introduction of self-selecting fee systems will benefit all economic entities, that is, Pareto improvement.

The purpose of introduction of the ETC commuting discount must expedite the spread of ETC as a mode of collection of the highway fee. In order to achieve this, users must be presented with long-term incentives for installing ETC devices in their automobiles. The highway uses have interdependence property. Therefore, it is not always the case that the introduction of a self-selecting fee system benefits users. Road congestion is a well-known example of the externality which occurs due to the interdependence property. In fact, following the introduction of the ETC commuting discount, road congestion was evident in highway sections and during hours that had little congestion previously. The Japanese highway policy needs to mitigate this disadvantage of the ETC commuting discount with immediate effect.

Owing to the above reason, it is necessary to comprehend the relations between the ETC commuting discount and the variations in highway congestion, in order to arrive at consensus. This study applies the traditional bottleneck congestion model, which was conceived by Vickrey [2] and extended Arnott *et al.* [3], to incorporate the ETC commuting discount policy.

2 Applying the bottleneck congestion model to self-selecting road pricing

2.1 Bottleneck congestion and optimal fee

For the sake of simplicity, this model is based on the following assumptions: The total number of commuters is fixed at $\overline{N}$, and all commuters travel the same distance on the highway in the morning peak period and pay the highway fee at the off-ramp. In order to minimize their travel costs, commuters can select their fee systems from the following two options.

(i) normal fee system: τ for each commuting

(ii) ETC discounted fee system: $(1-\delta)\tau$ for each commuting in the discounted period and τ for each commuting outside of the discounted period, with extra fixed costs for the ETC device

The bottleneck capacity is denoted by s. The travel time at which a commuter departs at t is denoted as

$$T(t) = \overline{T} + T^{\omega}(t), \tag{1}$$

where $\overline{T}$ is the travel time which is independent of the traffic congestion from home to office and $T^{\omega}(t)$ is the waiting time in the bottleneck queue. Assuming that $\overline{T} = 0$, the travel time is represented as $T(t) = Q(t)/s$, where $Q(t)$ denotes the queue that a commuter who alights at t faces at the bottleneck. The departure rate of commuters at t is given by $r(t)$.

The variation of queue is formulated as follows

$$\frac{dQ(t)}{dt} = \begin{cases} 0 & Q(t) = 0 \text{ and } r(t) \leq s \\ r(t) - s & r(t) \geq s \end{cases}. \tag{2}$$

The travel cost of commuters consists of the following costs: the travel time, time early and time late costs and highway fee.

$$C(t) = \alpha(travel\ time) + \beta(time\ early) + \gamma(time\ late) + fee, \tag{3}$$

where α, β, and γ are the shadow values of travel time, time early, time late respectively. The relations between these values are assumed as $\beta < \alpha < \gamma$, as given in Small [4].

We assume that all commuters wish to arrive at work at t^*. Let t_n be the departure time for which a commuter arrives at work on time: then $t_n + T(t_n) = t^*$. If a commuter departs earlier than t_n, he is early by $t^* - t - T(t)$, while if he departs later than t_n, he is late by $t + T(t) - t^*$. The travel costs of commuters are expressed as

$$C(t) = \begin{cases} \alpha T(t) + \beta(t^* - t - T(t)) + \tau(t) & (t \leq t_n) \\ \alpha T(t) + \gamma(t + T(t) - t^*) + \tau(t) & (t \geq t_n) \end{cases}, \tag{4}$$

where $\tau(t)$ denotes the fee which is charged on commuters who depart at t.

An equilibrium when $\tau(t) = \tau$ through the morning peak period is solved as the benchmark for various highway fee polices. The fixed fee equilibrium is defined since commuters are not incentivised to change their departure times. Let the queue continue from t_0 to t_e. Therefore, the morning peak period equals the total number of commuters divided by the bottleneck capacity.

$$t_e - t_0 = \frac{\overline{N}}{s} \tag{5}$$

The first and last commuters do not face a queue. The travel cost for the first and last commuters are simplified from equation (4) as shown below

$$C(t_0) = \beta(t^* - t_0) + \tau, \tag{6}$$

$$C(t_e) = \gamma(t_e - t^*) + \tau, \tag{7}$$

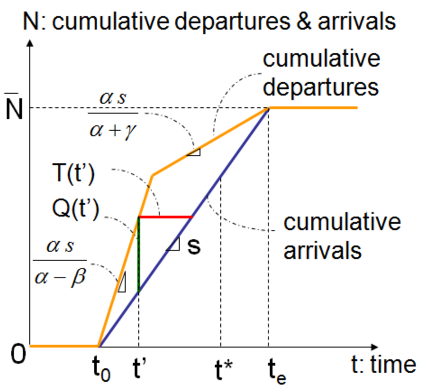

Figure 1: Equilibrium under the fixed fee.

Furthermore, if travel costs of all commuters should equal each other in this equilibrium then the departure time and travel cost are derived as

$$t_0 = t^* - \frac{\gamma}{\beta+\gamma}\frac{\overline{N}}{s},\ t_n = t^* - \frac{\beta\gamma}{\alpha(\beta+\gamma)}\frac{\overline{N}}{s},\ t_e = t^* + \frac{\beta}{\beta+\gamma}\frac{\overline{N}}{s} \tag{8}$$

$$C = \frac{\beta\gamma}{\beta+\gamma}\frac{\overline{N}}{s} + \tau \tag{9}$$

Travel time and departure rate are calculated as follows.

$$T(t) = \begin{cases} \frac{\beta}{\alpha-\beta}(t-t_0) & for\ t \in [t_0, t_n] \\ \frac{\gamma}{\alpha+\gamma}(t_e - t) & for\ t \in [t_n, t_e] \end{cases} \tag{10}$$

$$r(t) = \begin{cases} \frac{\alpha}{\alpha-\beta}s & for\ t \in [t_0, t_n] \\ \frac{\alpha}{\alpha+\gamma}s & for\ t \in [t_n, t_e] \end{cases} \tag{11}$$

The equilibrium which is characterized by the above equations is depicted in figure 1. The horizontal axis is a time scale, and the vertical axis is a cumulative automobile number. The vertical gap between the cumulative departures and cumulative arrivals functions is equal to the queue length. The horizontal gap corresponds to the travel time. Hence, the total social loss of bottleneck congestion, i.e. the total travel time, is calculated by the area between the two functions. Vickrey [2] insisted that social optimal is achieved by charging the time varying fee that corresponds to the travel time cost $\alpha T(t)$. Then optimal charging does not reduce the travel cost of commuters; however it eliminates queue and increases fee revenue.

2.2 Discount coarse fee

In this subsection, the effect of introducing discounts on coarse fee on highway use is investigated by using the above bottleneck congestion model to understand the self-selecting fee system. Coarse fees do not naturally translate into discounts. Instead, they refer to an additional fee to mitigate congestion. Figure 2 shows an equilibrium imposing additional coarse fee for heavy-congestion periods, as given in Arnott *et al.* [3]. On comparison with figure 1, we find that the part of social loss resulting from queuing time is converted to highway fee revenue to reduce highway congestion. Laih [5] said most effective n step fee achieve n/(n+1) efficiency compared with social optimal fee.

Arnott, de Palma and Linsey assumed a mass of automobile rush to the toll gate when the fee changed discontinuously and the order to pass the gate was decided randomly. This phenomenon is drawn as a right angle departure rate function which starts at t^-. The number of commuters included in mass is $2\delta_t \tau s/(\alpha+\gamma)$ at t^-. Commuters form queue instantaneously. Subsequently, a new commuter does not join the queue until the queue reduces such that their travel cost is equal to the equilibrium travel cost. Step fees are advantageous as they can be easily levied; however, in general, the amounts levied in this manner are inaccurate. Further, discontinuous variation in fee leads to confusion. However, an additional coarse fee appears to be reasonable.

On the other hand, a discount coarse fee may be inconsistent during the peak period. However, the ETC commuting discount which has similar features to the discount coarse fee has been executed even when the application of the policy is limited to a relatively uncongested area however congestions are occurred unobserved sections and during hours before introduction of the ETC commuting discount. Therefore, we investigate the adverse effect of introducing a discount coarse fee.

All commuters who pass the toll gate in the discount period can save δ of the fee. Let the discount period be $\left[t^-, t^+\right]$ and let t_n^-, t_n^+ denote the exact departure times for which commuters arrive on t^-, t^+. Herein, t_n^-, t_n^+ are satisfied with $t_0 < t_n^- < t_n < t_n^+ < t_e$. The travel costs are formulated as

$$C(t) = \begin{cases} \alpha T(t) + \beta(t^* - t - T(t)) + (1-\delta_t)\tau & for\ t \in [t_0, t_n] \\ \alpha T(t) + \gamma(t + T(t) - t^*) + (1-\delta_t)\tau & for\ t \in [t_n, t_e] \end{cases} \tag{12}$$

where $\delta_t \begin{cases} = 0 & for\ t \in \left[t_0, t_n^-\right], \left[t_n^+, t_e\right] \\ \neq 0 & for\ t \in \left[t_n^-, t_n^+\right] \end{cases}$

As shown in the previous subsection, travel costs are equal among all commuters such that the departure times, travel costs, and travel times can be given as

$$t_0 = t^* - \frac{\gamma}{\beta+\gamma}\frac{\overline{N}}{s}, \quad t_n = t^* - \frac{\beta\gamma}{\alpha(\beta+\gamma)}\frac{\overline{N}}{s} - \frac{\delta_t \tau}{\alpha}, \quad t_e = t^* + \frac{\beta}{\beta+\gamma}\frac{\overline{N}}{s} \tag{13}$$

$$t_n^- = \frac{\alpha-\beta}{\alpha}t^- + \frac{\beta}{\alpha}t_0 - \frac{\delta\tau}{\alpha}, \qquad t_n^+ = \frac{\alpha+\gamma}{\alpha}t^+ - \frac{\gamma}{\alpha}t_e - \frac{\delta_t\tau}{\alpha} \tag{14}$$

where t_n^-, t_n^+ have different values of $\delta_t \neq 0$ or $=0$, depending on whether there is discount or there is no discount.

$$T(t) = \begin{cases} \frac{\beta}{\alpha-\beta}(t-t_0) & for\ t \in [t_0, t_n^-] \\ \frac{\beta}{\alpha-\beta}(t-t_0) + \frac{\delta_t\tau}{\alpha} & for\ t \in [t_n^-, t_n] \\ \frac{\gamma}{\alpha+\gamma}(t_e-t) + \frac{\delta_t\tau}{\alpha} & for\ t \in [t_n, t_n^+] \\ \frac{\gamma}{\alpha+\gamma}(t_e-t) & for\ t \in [t_n^+, t_e] \end{cases} \tag{15}$$

$$C = \frac{\beta\gamma}{\beta+\gamma}\frac{\overline{N}}{s} + \tau \tag{16}$$

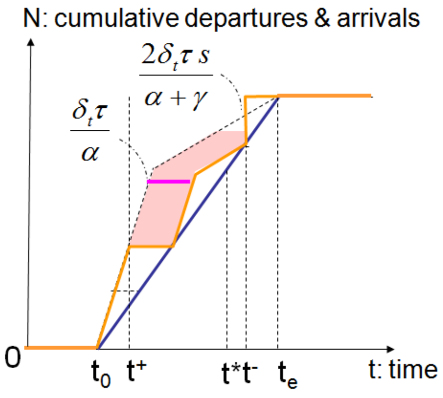

Figure 2: Additional coarse fee.

Figure 3 shows that the travel times of commuters who pass the toll gate in the discounted period are prolonged corresponding to the discount on fee, given by: $\delta_t\tau/\alpha$. In contrast, in figure 1 on the equilibrium condition, the fee fixed, i.e. τ . However, the travel costs of commuters do not change through the peak period; therefore, the total social loss increases in proportion to the decrease in fee revenue. At the start of discount, i.e. at t^-, a mass of automobiles, $2\delta_t \tau s/(\alpha - \beta)$, occur confusion at the bottleneck. The introduction of a discounted coarse fee causes additional congestion in a manner that is opposite to the effect of an additional coarse fee, as revealed by a comparison between figures 2 and 3.

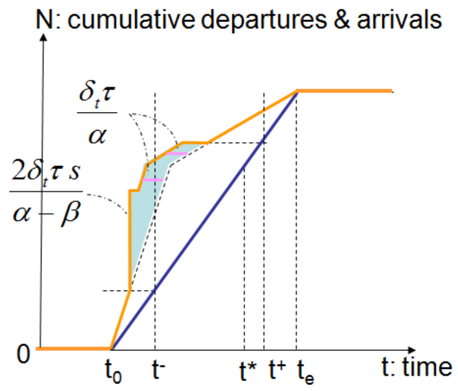

Figure 3: Discount coarse fee.

2.3 ETC commuting discount fee system as a self-selecting pricing system

We assume that the difference between ETC and non-ETC users is only the frequency of highway use and the other users' factors such as value of time are indifference. ETC users get a discount of $\delta_t \tau$ within the discount period $[t^-, t^+]$. Let k=E represent an ETC user, and k=N denote a non-ETC user. For simplicity, if we neglect the time saved in toll collection at the gate, then waiting times of queue would be in common to ETC and non-ETC users.

$$C^k(t) = \begin{cases} \alpha T(t) + \beta(t^* - t - T(t)) + (1-\delta_t^k)\tau & for\ k \in (E,N), t \in [t_0, t_n] \\ \alpha T(t) + \gamma(t + T(t) - t^*) + (1-\delta_t^k)\tau & for\ k \in (E,N), t \in [t_n, t_e] \end{cases} \tag{17}$$

where $\delta_t^k \begin{cases} = 0 & for\ k = E, t \in [t_0, t_n^-], [t_n^+, t_e] \\ \neq 0 & for\ k = E, t \in [t_n^-, t_n^+] \\ = 0 & for\ k = N, t \in [t_0, t_e] \end{cases}$.

(1) Case of $(t^+ - t^-)s \geq N^E$

Let us begin with case in which the number of ETC users is less than the capacity of the discount period. This case corresponds to a relatively low discount rate, expensive ETC device, large capacity of bottleneck, long discount period, early spread period of ETC device and so on. The equilibrium holds under the condition that no commuter has an incentive to change his/her departure time in order to reduce travel costs.

$$t_0 = t* - \frac{\gamma}{\beta+\gamma}\frac{\overline{N}}{s},\ t_n = t* - \frac{\beta\gamma}{\alpha(\beta+\gamma)}\frac{\overline{N}}{s},\ t_n = t* - \frac{\beta\gamma}{\alpha(\beta+\gamma)}\frac{\overline{N}}{s}, \tag{18}$$

$$t_n^- = \frac{\alpha-\beta}{\alpha}t^- + \frac{\beta}{\alpha}t_0, \quad t_n^+ = \frac{\alpha+\gamma}{\alpha}t^+ - \frac{\gamma}{\alpha}t_e \tag{19}$$

$$T(t) = \begin{cases} \dfrac{\beta}{\alpha-\beta}(t-t_0) & for\ t \in [t_0, t_n] \\ \dfrac{\gamma}{\alpha+\gamma}(t_e - t) & for\ t \in [t_n, t_e] \end{cases} \tag{20}$$

$$C^E = \frac{\beta\gamma}{\beta+\gamma}\frac{N}{s} + \left(1-\delta_t^E\right)\tau \quad for\ t \in [t_0, t_e] \tag{21}$$

$$C^N = \frac{\beta\gamma}{\beta+\gamma}\frac{N}{s} + \tau \qquad for\ t \in [t_0, t_e] \tag{22}$$

In the equilibrium illustrated in figure 4, only the travel cost of ETC users decreases within the discount time period. The difference between the travel costs of ETC and non-ETC users arise from the following mechanism. ETC users will try to pass the toll gate within the discount period, while non-ETC users are not interested in the discount period because they cannot enjoy the ETC commuting discount. From the given condition, i.e. $\left(t^+ - t^-\right)s \geq N^E$, all ETC users can use the highway within the discount period, including some non-ETC users. ETC users change their departure time within the discounted period and non-ETC users change their departure time within both discounted and non discounted periods in order to reduce their travel costs. The equilibrium is valid when no commuters can find an alternative departure time to reduce his/her travel costs. As a result, all ETC users pass the toll gate within the discounted period. Travel times for ETC and non-ETC users are exactly the same corresponding to each departure time in the equilibrium; therefore, a commuter cannot distinguish ETC users from other commuters except for toll gate. Even if the highway fee is discounted, additional congestion will not occur because self-select pricing will discriminate ETC users from others invisibly.

(2) Case of $\left(t^+ - t^-\right)s \leq N^E$

Herein, the number of ETC users is more than the capacity of the discounted period. This case may be caused by a relatively high discount rate, cheap ETC device, small capacity of bottleneck, short discount period, late spread period of ETC device and so on. The equilibrium is also solved under the condition that no commuter has an incentive to change his/her departure time to reduce travel costs.

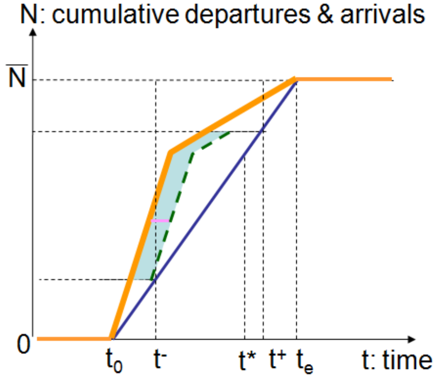

Figure 4: Self-select fee in case (1).

$$t_0 = t^* - \frac{\gamma}{\beta+\gamma}\frac{\overline{N}}{s},\ t_n = t^* - \frac{\beta\gamma}{\alpha(\beta+\gamma)}\frac{\overline{N}}{s} - \frac{\delta_t^E \tau}{\alpha},\ t_e = t^* + \frac{\beta}{\beta+\gamma}\frac{\overline{N}}{s} \tag{23}$$

$$t_n^- = \frac{\alpha-\beta}{\alpha}t^- + \frac{\beta}{\alpha}t_0 - \frac{\delta_t^E\tau}{\alpha},\ t_n^+ = \frac{\alpha+\gamma}{\alpha}t^+ - \frac{\gamma}{\alpha}t_e - \frac{\delta_t^E\tau}{\alpha} \tag{24}$$

where t_n^-, t_n^+ have two values corresponding to $\delta_t^E \neq 0$ or $=0$ at t^-, t^+ .

$$T(t) = \begin{cases} \frac{\beta}{\alpha-\beta}(t-t_0) & for\ t \in [t_0, t_n^-] \\ \frac{\beta}{\alpha-\beta}(t-t_0) + \frac{\delta_t^E\tau}{\alpha} & for\ t \in [t_n^-, t_n] \\ \frac{\gamma}{\alpha+\gamma}(t_e-t) + \frac{\delta_t^E\tau}{\alpha} & for\ t \in [t_n, t_n^+] \\ \frac{\gamma}{\alpha+\gamma}(t_e-t) & for\ t \in [t_n^+, t_e] \end{cases} \tag{25}$$

$$C^E = \frac{\beta\gamma}{\beta+\gamma}\frac{N}{s} + \tau \quad for\ t \in [t_0, t_e] \tag{26}$$

$$C^N = \frac{\beta\gamma}{\beta+\gamma}\frac{N}{s} + (1+\delta_t^E)\tau \quad for\ t \in [t_0, t_e] \tag{27}$$

As shown in the equilibrium in figure 5, only the travel costs of non-ETC users increase discounted time period. The difference between travel costs of ETC and non-ETC users arise from the following mechanism. ETC users try to pass the toll gate within discounted period; however, a section of ETC users cannot do so because the number of ETC users is more than the capacity of bottleneck in discounted period. Then, ETC users extend the queue within the discounted period until their travel costs equal to the travel cost in the non-discounted period. On the other hand, non-ETC users do not need to pass the gate within the discount period; furthermore, they do not attempt to extend the queue within the discount period. Therefore, all non-ETC users pass the toll gate outside of the discount period. In the equilibrium, all commuters who pass the toll gate within the discount period are ETC users and commuters who do so outside the discounted period are ETC and non-ETC users.

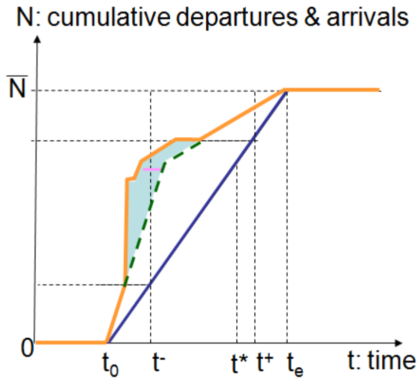

Figure 5: Self-select fee in case (2).

It must be noted that in this case, if non–ETC users do not commute within the discount period, then the travel cost of all commuters is exactly the same in the equilibrium even if a section of ETC users obtain a discount highway fee. The outline of figure 5 is the same as figure 3. This means that the merit of self-select pricing diminishes by spread of ETC use.

3 Concluding remarks

This study analyses the ETC commuting discount on highway fee by the application of the traditional bottleneck congestion model in order to determine a self-selecting fee system. From the results, it can be inferred that the self-select pricing mechanism eliminates the negative effects of granting discount in the peak period; however, the mechanism may not work when ETC use becomes widespread. The conditions are based on the number of ETC users, capacity of bottleneck, and length of the discounted period.

It is difficult to grasp the long term prospects of the ETC discount policy. The purpose of this policy is to rapidly spread ETC use. In the early stages, the merit of ETC use must be ensured by giving differential discounts for ETC use; further, no commuters must be disadvantaged thereby ensuring a good response to this policy. However, if ETC is widely in the later stages, then the merit of discount is nullified by the increase in congestion. Moreover, non-ETC users will have a disadvantage in terms of their choice of departure time because if they want to benefit from the discounted period, they will have to wait in a long queue without obtaining any discount or buy an ETC device to avoid higher travel costs. As a result, commuters will not benefit even if the highway fee is reduced by the discount amount and ETC use spreads widely.

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