Effect of Off-peak Hour Toll Reduction on Toll Roads

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A transport economic model was developed to evaluate changes in total travel costs on congested toll roads by dispersing peak-hour traffic to the pre-peak hours or post-peak hours with a toll discount. To empirically analyze the effectiveness of the early-morning and daytime toll discount, early departure cost and late arrival cost were estimated and traffic data of Metropolitan Expressway Route 3 was assigned. The result shows that an early-morning toll discount, shifting the peak-hour traffic to the pre-peak hours, produces a long-lasting effect of congestion mitigation starting from the peak-hours. It is empirically presented that an early-morning toll discount is effective in cutting travel costs.

Keywords*: transport economic model, road pricing, congestion pricing, time-of-day pricing, toll discount, travel cost, schedule cost, early departure cost and late arrival cost*

1. Introduction

Generally, road traffic volume is heaviest and most congested during peak, morning and evening hours, and lightest during non-peak, early-morning, daytime and late night hours. Accordingly, from the perspective of the effective use of road resources, shifting traffic volume from peak, congested hours to non-peak, non-congested hours should mitigate road congestion.

While for toll roads, reducing the toll for less-congested, non-peak hours should shift traffic volume from peak congestion hours to non-peak congestion hours, and in turn mitigate road congestion. The spread of Intelligent Transportation Systems (ITS), including Electronic Toll Collection (ETC), has raised expectations that road demand can also be controlled through hourly toll charges.

This study develops a model based on the transport economics for the time shift of road users and the mechanisms for related societal benefits when levying a toll discount. Using Tokyo Metropolitan Expressway traffic data for empirical analysis, this study then develops a basic theory for setting toll charges tailored to specific hours of the day.

2. Overview of previous research and correlation with this study

2.1. Previous researches on selection behavior of departure time

A great number of previous researches have reported that departure time shift had been observed by introducing time-of-day pricing on toll roads (e.g. [11] [12] [13] [14] [15]). And some researches have attempted to make a quantitative estimate of the number of drivers who shifted their departure times (e.g. [16] [17]). These researches use travel time, toll and shifted departure time to set a utility function, construct a model and estimate the number of vehicles that shifted departure time. However, none of these studies have evaluated change of travel cost including early departure or late arrival cost.

2.2. Previous researches on departure time choice model combined with traffic simulation

Research studies that combine the behavioral model selecting the departure time on the congested roads with a traffic simulation have been carried on to reduce travel costs through an hourly charging. Our study belongs to this category of research study.

Previously, several research studies have been conducted on travel behavior at peak times. Past studies have formulated models on behavioral selection that find workers with the same work start time (or desired arrival time) select their departure time by considering the tradeoff between scheduling cost and congestion cost (time cost). “Scheduling cost” here refers to the opportunity cost of the waiting period resulting from early arrival (early-arrival cost) or the penalty for late arrival (late-arrival cost).

With respect to peak times, the travel behavior model can largely be separated into two approaches depending on the method for expressing congestion. First, the Henderson [1] (1981) “Flow Congestion Model,” which found that travel time increases with traffic volume increases using the QV [traffic volume-speed] Formula, and second, the Vickrey (1969) [2] and Arnett et al. (1990) [3] "Bottleneck Model," where traffic volume exceeding traffic capacity at bottlenecks, such as intersections, created a backup starting at the bottleneck which in turn lead to longer travel times.

The assessment of congestion charge effects also varies, again, depending on the method for expressing congestion. In the Flow Congestion Model, the welfare of users deteriorated due to congestion charges, which result in an increased cost burden from the combination of time cost and schedule cost. In contrast, in the Bottleneck Model, congestion charges resolved economic loss resulting from congestion without deteriorating the welfare of users.

Various traffic simulations have also been conducted using traffic data. For example, Mun (2005) created a model that integrates both the Flow Congestion Model and Bottleneck Model (using a QV [traffic volume-speed] Formula or the segment of road leading to the bottleneck to find traffic volume increases lead to increased travel time, while in the bottleneck, a back up occurs when traffic volume exceeds traffic capacity, resulting in increased travel time) in conducting a traffic simulation targeting the Meishin Expressway to define an appropriate standard for congestion charges.

Additionally, Koshi (2007) conducted a learning simulation based on the Bottleneck Model, where users decide their departure time on the day of departure according to traffic conditions from the previous day, and found that congestion charges are effective in mitigating traffic congestion.

While the target of the research studies mentioned above is a single road segment, Heydecker, et al. (2005) proposes a traffic volume distribution model which leads to an equilibrium solution including route selection on a road network through a dynamic equilibrium model, a type of bottleneck model. However, this research study does not go further than model proposal.

2.3. Cost items and unit cost in previous research studies

Research studies conducted until now have defined the generalized travel cost of travelers as the sum of 1) travel time cost; 2) scheduling cost (early-arrival or late-arrival cost); and 3) toll charges except the model that Heydecker, et al. (2005) [10] which includes early departure cost. Additionally, these studies have used the concept of user equilibrium, where departure time is distributed so that the generalized travel cost of travelers at each departure time equals the same cost.

Among previous research studies, only Small (1982) [8] estimated empirically the unit cost of each cost using observed data. In other research studies, each cost was assumed as an exogenous value. In these cases, Small's (1982) [8] estimation results are predominantly incorporated in many studies. Each study also shares the common finding that early arrival cost (β) < travel time cost (α) < late arrival cost (γ). Table 1 provides a quick glance at the unit cost of each cost for principal research studies conducted previously.

In addition, Small (1982) [8] sought the arrival time and schedule cost using a questionnaire survey on commuter trips. Although this represents one approach, it represents asserted values, and does not necessarily match with actual behavioral patterns. Furthermore, data from Small's approach cannot be directly applied to traffic volume on the road because in reality there is variety of travel purposes.

Table 1. Unit costs in previous research

(Each value represents yen per minute)

	α	β	γ
Vickrely (1969) [2]	3.0	1.5	6.0
Henderson (1981) [1]	-	-	-
Small, et al. (1982) [8]	<u>12.2</u>	<u>7.5</u>	<u>29.2</u>
Arnett, et al. (1990) [3]	16.0	9.8	38.0
Koshi (1998) [4]	-	-	-
Heydecker, et al. (2005)*	-	-	-
Koshi (2007) [5]	140.0	60.0	200.0
Mun (2005) [6]	33.3	13.3	70.0

NOTE 1: "α" is the time delay unit cost; "β" is the early arrival unit cost; and "γ" is the late arrival unit cost
NOTE 2: *: early departure cost is included.
NOTE 3: "-" indicates a study where only a model was formulated, but no numerical analysis was conducted.
Note 4: 1 US dollar = 115 Japanese yen
Note 5: Underlined values represent empirical estimates using actual observed data, while non-underlined values hypothesize each unit cost as exogenous values.

2.4. Correlation with this Study

In previous research studies, each model presumed that there is only one desired arrival time at the destination for road users. Additionally, these studies also attempted to find the optimal solution for charges to ensure the lowest possible total travel costs. In contrast, this study is unique in the research studies, because it

(1) Presumes there are multiple desired arrival times at the destination, rather than a uniform desired time.
(2) Does not attempt to find the optimal solution, but rather attempts to find the total travel costs and changes of travel behavior when toll charges are levied.
(3) Sets the flowing four types of schedule costs instead of commonly used ones in previous research.
    a) Early departure cost: a cost resulted from behavior change to early departure
    b) Early arrival cost: a cost resulted from behavior change to early arrival
    c) Late departure benefit: a benefit of timesaving resulted from late departure
    d) Late arrival cost: a cost resulted from late arrival

(4) Includes the four schedule costs above in the study's model
(5) Does not presume the unit cost of the four schedule costs above, but rather uses observational data for estimating these values.
(6) Evaluates the economic effect in the context of the actual situation on the tolling measures by its characteristics.

3. Development of a user equilibrium model

3.1. Establishing generalized travel cost

Generalized travel cost was defined as consisting of 1) trip time cost; 2) early arrival cost or late arrival cost; 3) early departure cost or late departure cost; and 4) toll charges. Although previous studies have not incorporated early departure cost and late departure cost into their models, this study followed the recommendation of Heydecker, et al. (2005) and Koshi (1998) [4] to include early departure cost in its model and include benefits derived from late departure as early departure cost with a negative value according to the recommendation of Koshi (1998).

Although each unit cost differs according to individual and societal conditions in reality, this study developed a model that hypothesizes all road users have the same unit costs for simplicity. For the purposes of this study, generalized travel cost of travelers and generalized travel cost for evaluating social cost were expressed using the following formulas.

Generalized travel cost of travelers =
(Travel Time Cost)
+ (Early Departure Time Cost or Late Departure Cost)
+ (Early Arrival Time Cost or Time Delay Cost)
+ (Toll Charges)

Generalized travel cost for evaluating social cost=
(Travel Time Cost)
+ (Early Departure Time Cost or Late Departure Cost)
+ (Early Arrival Time Cost or Time Delay Cost)

Here, late departure cost is expressed in a negative value. Since toll charges are transfer cost, they are not included in generalized travel cost for evaluating social cost.

3.2. Establishing desired arrival time and desired departure time

Previous research studies either assumed the desired arrival time of road users to be the same (for example, Koshi [1998]) or did not establish the desired arrival time (for example, Takeuchi [2008]). Each road user in the real world, however, has different desired arrival times. The road segment and travel time/distance from the bottleneck to the destination also vary with the individuals. In considering a more realistic hypothesis, the following conditions were applied.

When there are no fluctuations in travel time, it can be surmised that present road users set their departure time so that they arrive at their desired arrival time. Accordingly, the present departure time represents the desired departure time, and users'daily lives and work schedules are based on this departure time. Given this perspective, the present time of passage at all points along the route also represents the desired time of passage. Therefore, departing early prior to these times will result in schedule conflicts, causing loss, while departing late will result in leeway in the schedule, causing benefit.

In this study, the present time of passage at the downstream endpoint on road segments under review for hourly toll charges also represents the desired time of passage of road users.

3.3. Conditions for user equilibrium

Based on concept of user equilibrium, this study hypothesized that an equilibrium will be reached where the generalized travel cost of travelers with the same desired departure time becomes the same regardless of departure time, and each individual user cannot reduce his generalized travel cost regardless of which time they shift to (Wardrop's First Principle of Equilibrium). Consequently, taking early morning off-peak toll discount for example, the following conditions were presumed.

a) There are two departure times X_A and X_B, where X_A is peak hours and X_B is early morning off-peak hours.
b) The travel times are T_A and T_B, where travel time is longer during peak hours than during off-peak hours, thus $T_A > T_B$.
c) Traffic volume for each time is Q_A and Q_B.

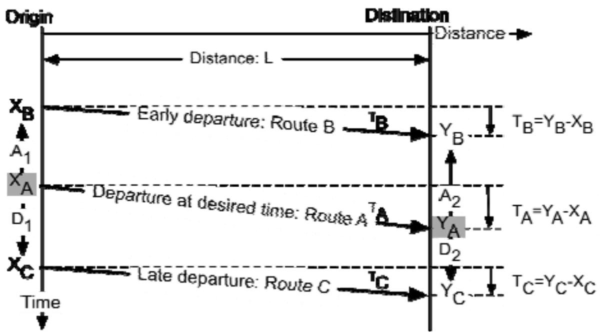

Figure 1. Conceptual diagram of the spatial-temporal time shift

In this setting, an early departure cost will be incurred when a road user who originally selected X_A changes their departure time to X_B. As a result, under existing conditions, X_B will not be selected as the departure time, despite a shorter travel time. This situation is illustrated in Figure 1. Each symbol from Figure 1 is expressed as thus:

X_A, X_B, X_C: Departure time using spatial-temporal route A, B, C

Y_A, Y_B, Y_C Arrival time using spatial-temporal route A, B, C

τ_A, τ_B, τ_C Toll charge (yen) of spatial-temporal route A, B, C

T_A, T_B, T_C: Travel time (minutes) using route A, B; where $T_A=Y_A-X_A$, $T_B=Y_B-X_B$, $T_C=Y_C-X_C$. Each is a function of traffic volume; $T_A= T_{1A}(Q_A)$, $T_B=T_{1B}(Q_B)$, $T_C=T_{1C}(Q_C)$

A_1: $A_1=X_A-X_B$; Early departure time (minutes) when changing from route A to route B

A_2: $A_2=Y_A-Y_B$; Early arrival time (minutes) when changing from route A to route B

D_1: $D_1=X_A-X_C$; late departure time (minutes) when changing from route A to route C

D_2: $D_2=Y_A-Y_C$; late arrival time (minutes) when changing from route A to route C

Here, generalized travel cost of travelers was expressed as follows:

a) When departing at desired time and arriving at the destination at desired time
$P_A = \alpha T_A + \tau_A$

b) When departing early and arriving at the destination early
$P_B = \alpha T_B + \tau_B + \beta_1 A_1 + \beta_2 A_2$

c) When departing late and arriving at the destination late
$P_C = \alpha T_C + \tau_C - \gamma_1 D_1 + \gamma_2 D_2$

Each symbol from above expresses the following meaning:

P_A, P_B, P_C : generalized travel cost of travelers (yen) when using route A,B, C
α: Unit cost of travel time (yen / minutes)
β_1: Unit cost of early departure (yen / minutes)
β_2: Unit cost of early arrival (yen / minutes)
γ_1: Unit cost of late departure (yen / minutes)
γ_2: Unit cost of late arrival (yen / minutes)

β_1, β_2, γ_1, γ_2 represent the schedule cost. The schedule costs occur both at departure and at arrival.

$\tau_A = \tau_B$ and $P_A < P_B$ for road users departing at X_A time before the early morning toll discount is applied. When the early morning hour toll discount is applied, $\tau_A > \tau_B$ and road users who meet $P_A > P_B$ will move their departure time to X_B (time shift). At this time, equilibrium will be reached at the time shift volume where generalized travel cost of travelers P_A and P_B become the same, regardless of selecting departure time XA or XB. That is to say, There exists Q_A*and Q_B* where P_A*=P_B*, and the travel time at that time becomes T_A*, T_B*. Figure 2 illustrates the concept of departure time selection.

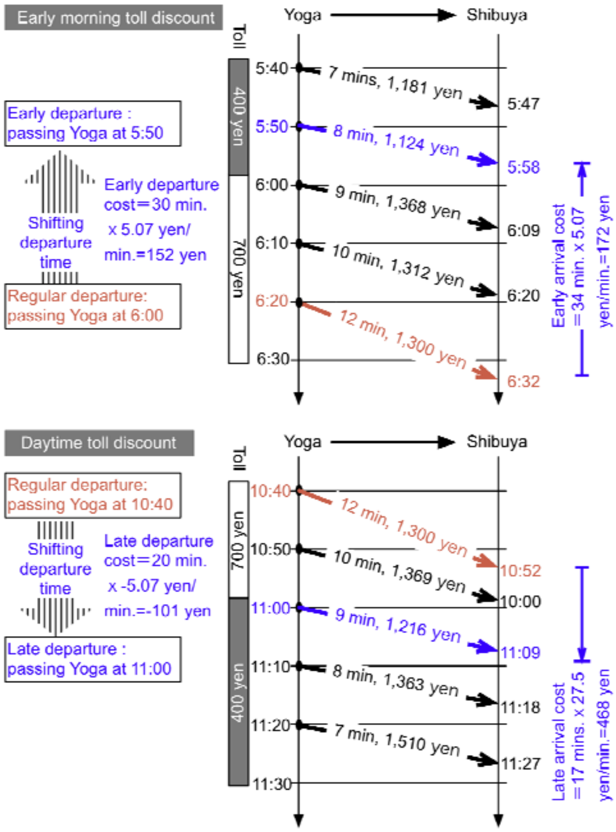

Figure 2. Illustration of generalized travel cost of travelers at the time of the time shift

Numerical values indicated in the middle of the arrow express travel time and generalized travel cost of travelers. For example, if toll charges during the 5am hour are discounted from 700 yen to 400 yen, departing at 5:50 instead of 6:20 will make the lowest generalized travel cost of travelers.

4. Setting target road for analysis and associated traffic conditions

4.1. Target road segment and traffic jams

This study targets the Tokyo Metropolitan Expressway Route 3 for model analysis. (See Figure 3)

Metropolitan Expressway Route 3 experiences traffic jams from the 6am hour until 10am starting from the vicinity of the Ikejiri exit to the Shibuya on-ramp. The traffic jam peaks between 7am and 8am. Afterwards, the traffic jam continues until 11am followed by almost no congestion from 11am to 12pm.

4.2. Segment traffic volumes and travel speeds

Metropolitan Expressway Route 3 is a 2-lane (for each direction) motorway. Its eastbound traffic volume is heaviest between the hours of 6am and 8am, with peak traffic volume approximately 3,500 vehicles per hour. Whereas, travel speeds are slowest at around 10am. Therefore, traffic volume and travel speed are not proportionally related, as a time disparity occurs where travel speeds are actually slowest after peak hourly traffic volume occurs.

National Highway Route 246 which runs parallel to Metropolitan Expressway Route 3 is a 3-lane (for each direction) all-purpose highway. It has a near-constant daily traffic volume of approximately 2,000 vehicles per hour and travel speeds of 20 to 30km per hour.

Figure 3 Target road segment
From Yoga to Shibuya on Route 3 of Tokyo Metropolitan Expressway Network (red lines)
Source: Metropolitan Expressway Co., Ltd

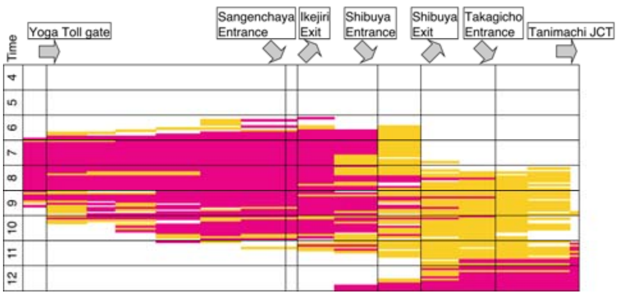

Figure 4. Traffic jam conditions by time and segment on metropolitan expressway route 3 Shibuya line (eastbound)
SOURCE: Metropolitan Expressway Co., Ltd. Traffic Sensor Data (February 19, 2007)
Note 1: ■Traffic Jam, ■Congestion
Note 2: Above graph shows the traffic condition, identifying when and where in the expressway is congested with horizontal axis of location and vertical axis of time (4 am to 12 am). Red color areas, the yellow areas and white areas indicate the road segments and the periods where the traffic flows at slower than 20 km/h, slower than 40 km/h and faster than 40 km/h respectively.

4.3. Exiting/merging traffic volume

Connecting traffic from the Tomei Expressway and merging traffic from the Yoga on-ramp combine to account for 98% of all eastbound merging traffic volume on Metropolitan Expressway Route 3 (See table 2). Accordingly, this study applied a single route model that did not take into account traffic volume from on-ramps and exit-ramps along the eastbound lanes of Metropolitan Expressway Route 3.

Table 2. Merging traffic volumes (vet./h)

Time Period	Main line Traffic at Yoga Toll Gate	Sangenjaya-Ikejiri Entrance/Exit	
		Net Merging Traffic	Ratio
5:00 - 7:00	2,460	59	2%
10:00 - 12:00	1,986	48	2%

Note: Net Merging Traffic = Entering traffic – Exiting traffic

5. Travel time estimation model

It was necessary to estimate the travel times for the road segment in order to solve the above-mentioned User Equilibrium Model. Generally, the QV (traffic volume-speed) Formula is used to estimate the travel time of a segment of road, but the QV Formula does not cover the case of increasing travel times and decreasing traffic volume during traffic jams because under the formula travel time will uniformly increase with traffic volume. Therefore, the Block Density Method was used in this study.

5.1. Segments targeted for the model

Peak morning traffic jams occurring in the eastbound lanes of the Metropolitan Expressway Route 3 begin from the sag between Sangenjaya-Ikejiri Entrance/Exit and Shibuya exit. Yet, nearly all users (97% in 5:00-7:00 and 92% in 10:00-12:00) actually pass the Shibuya off ramp and pay a toll for total distance driven. Consequently, a target segment length of 15km was established in considering that the average value of distance driven on the Metropolitan Expressway Tokyo Line is similarly 15km.

The 8.0km-segment from the Yoga Toll Gate to the sag was the target segment of the Block Density Method model, while the remaining 7.0km segment was presumed as the segment of expressway where vehicles can travel unencumbered at the free flow speed.

5.2. Computational procedure

The Block Density Method model was conducted as the following steps.

i) Setting Block Length, Scan Time and Free Flow Speed

The road segment targeted for analysis was divided into unit blocks of distance. The unit distance (do: block length = 133m) was set as the distance moved at free flow speed (Vf = 80km/h) during the scan time (dot = 6 seconds). Specifically, this established do = Vf dot.

ii) Setting the Relationship of Traffic Volume / Density

The relationship of traffic volume (Qi) and density (Ki) for each block (i) was established, while critical density (Kick) and saturation (jam) density (Kji) were assigned as parameters. Critical traffic volume (Qci: block traffic capacity) was determined as Qci = Vf x Kc_i.

iii) Calculating the Moving Traffic Volume between Blocks

Traffic volume ($Q_{i+1,i}$) moving from the upstream block (i+1) to the downstream block (i) was calculated according to the traffic density of the downstream block (i) and upstream block (i+1), merging traffic volume of the downstream block (i), and diffusible (exiting) traffic volume of the upstream block (i+1).

5.3. Setting parameter values

Miscellaneous parameters were established to adjust for observed traffic where required, including the maximum flow rates for ordinary segments set at 3,600 vehicles per hour and 2,400 vehicles per hour for the bottleneck segment.

5.4. Setting traffic volume

10-minute interval merging traffic volume (traffic sensor data from February 19, 2007) observed bound for the upstream endpoint of the target segment (total volume connecting via the Tomei Expressway and merging from
Yoga on-ramp) was divided by scan time (dot) to establish the unit time merging traffic volume.

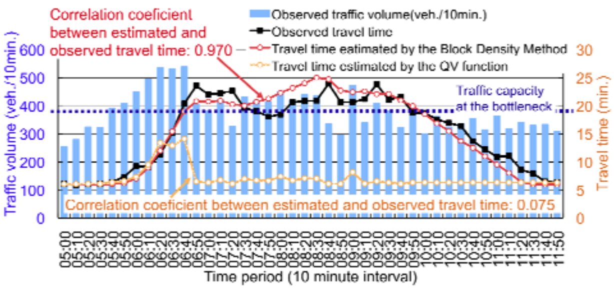

Figure 5. Comparisons of estimated values (block density method and QV formula) and observed values

NOTE 1: The reason for the discrepancy between the estimate from the Block Density Method and observed values is thought to be because there is another bottleneck located downstream from the Shibuya off-ramp.

NOTE 2: QV Formula estimate values are also included for reference.

5.5. Consistency of observed values and model values

Using the Travel Time Estimation Model, the travel time under the present conditions of no toll discount was estimated to conduct a comparison with observed values. As indicated in Figure 5, the estimated travel time calculated using the Travel Time Estimation Model closely matches observed values.

6. Estimating the various unit costs of time

6.1. Actual conditions of traffic volume time shift resulting from toll discounting

Although there is an example of using questionnaire survey data to measure the unit time cost of early departure and early arrival by Small et al (1982) [8], there are no examples of measuring these unit costs using actual driver behavioral changes data. However, the observed time shift percentage from a pilot program on tolling provides a clue.

An experiment on toll discounting was conducted on the Metropolitan Expressway in November 2007. During this experiment, a questionnaire survey on the changes of behavioral patterns with the introduction of the toll discount was conducted targeting the Metropolitan Expressway users. This survey found the following results.

a) An early morning off-peak toll discount (20% discount until 6:00am) led 2.9% of 6:00am traffic to shift to the 5:00am hour.

b) A daytime off-peak discount (20% discount after 11:00am) led 1.4% of 10:00am traffic to shift to the 11:00am hour.

6.2. Estimation methods for the various unit costs of time

This study attempted to find the unit costs of early departure and early arrival that match the observational data of the pilot program on toll discount.

Cost relating to time includes α, β_1, β_2, γ_1, and γ_2, whereas, observed data includes the above-mentioned 1) and 2). As not all of these variables can be solved as unknown numbers, the following assumption was made.

A) α represents the value of time. Previous research studies have established a value for α, while recent studies have used the Cost Benefit Manual [9], which stipulates that the average vehicle time value is 50 yen per minute.

B) β_1, β_2 represent the schedule cost relating to early departure, with β_1 occurring at departure and β_2 at arrival. Drivers are thought to experience both on the same trip, as $\beta=\beta_1=\beta_2$.

C) γ_1 represents the time value of late departure and is considered the time value of early departure from the opposite direction, as $\gamma_1=-\beta$.

Given this perspective, estimated schedule costs using the factually observed values 1) and 2) become β and γ_2, which are solvable.

Furthermore, as a simple hypothesis, the early departure and early arrival costs were set as the same value and late departure was set as the negative cost of early departure, or the benefit. Departing early would mean either giving up prior-to-departure activities or shifting these activities to a different time, and arriving early would mean waiting until the scheduled time or engaging in other activities. In addition, late departure would result in either spending longer time for prior-to-departure activities or engaging in activities planned for a different time. Thus, it is thought that activity changes as well as cost both differ for early departure and early arrival. Further quantitative research is left to future studies.

6.3. Estimating the unit cost of early departure and early arrival

Mun (2005) hypothesized the unit cost value β of early departure as 13.3 yen per minute [6]. A simulation was repeated starting with this value (13.3 yen/minutes) and with gradually smaller than the previous value each time until the percentage of the traffic shift from 6am to 5am was determined. 2.9% was found to be the final traffic shift at β of 5.07 yen per minutes. Considering it is the closest to the observational value in the pilot program, β was determined to be 5.07 yen/minutes. Also, $\gamma_1 = -\beta = -5.07$.

6.4. Estimating unit time cost of late arrival

As with estimating the unit time cost of early departure and early arrival, simulations were repeated changing the value gradually smaller from 100 yen per minute in order to seek the traffic volume time shift percentage from the 11:00am hour to the 10:00am hour. Simulation results showing 27.5 yen per minute achieved a similar traffic volume time shift percentage (1.4%) as observed during the pilot program on tolling. As a result, γ_2 was determined to be 27.5 yen per minute.

6.5. Unit costs of time

From the findings above, travel time cost and schedule costs were determined to be following time costs:

Travel time cost: $\alpha = 50$ yen/minutes
Unit Cost of early arrival: $\beta_1 = 5.07$ yen/minutes
Unit Cost of early departure: $\beta_2 = 5.07$ yen/minutes
Unit Cost of late departure: $\gamma_1 = -5.07$ yen/minutes
Unit Cost of late arrival: $\gamma_2 = 27.5$ yen/minutes

7. Assessing the effects of traffic flow improvement through hourly tolls

7.1. Assessing the effect of traffic flow improvement through early morning discount

7.1.1 Hours for toll discount and toll pricing. The 5am hour was targeted for toll discounting because the morning peak of eastbound traffic volume on the Metropolitan Expressway Route 3 occurs between the hours of 6am and 8am. Based on the current 5am toll charge of 700 yen, three toll discount scenarios were analyzed 1) 600 yen (14% discount), 2) 500 yen (29% discount) and 3) 400 yen (43% discount).

7.1.2 Results. The following results were achieved after conducting an analysis using the above-mentioned model to study the hours between 5am and 10am.

a) Shifts in Traffic Volume

As indicated in Figure 6, implementation of an off-peak discount for the 5am hour lead traffic volume to shift from the 6am hour to the 5am hour by 1) 1.4%, 2) 3.2% and 3) 5.2% respectively for each toll discount scenario. 10-minute changes in traffic volume for each toll discount rate are indicated in the Figure 6.

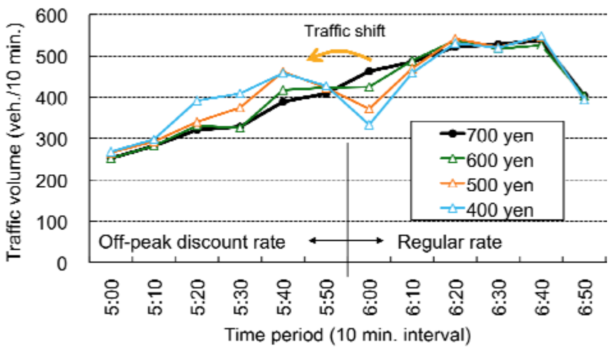

Figure 6. 10-minute changes in traffic volume for each toll discount rate of early morning discount

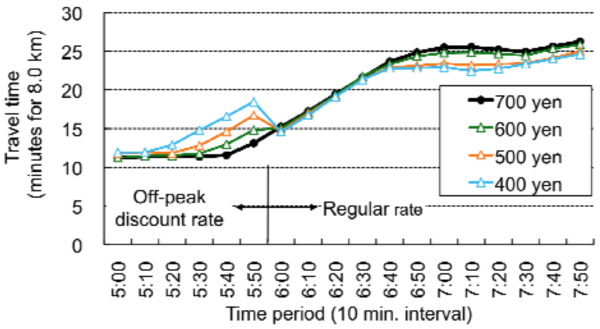

Figure 7. Changes in travel time for each toll discount rate of early morning discount

b) Congestion mitigation

Shifting traffic volume to the early morning hours leads to effective traffic congestion mitigation for the peak hours after 6am as well as later hours. Viewing changes in travel time in Figure 7, the travel time before 6 am went longer, whereas the travel time after 6 am went shorter. This time reduction continued in subsequent time slots.

The travel time for the hour before 6am when traffic volume is low became longer, but became shorter for the hours after 6am when traffic volume is heavy. So, the total time reduction is much lager than the total time increase. These effects create large benefit.

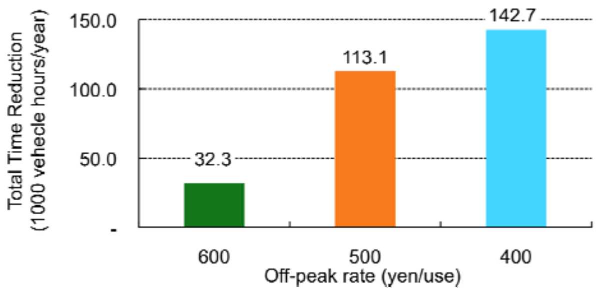

Figure 8. Travel time reduction for each toll discount rate of early morning discount

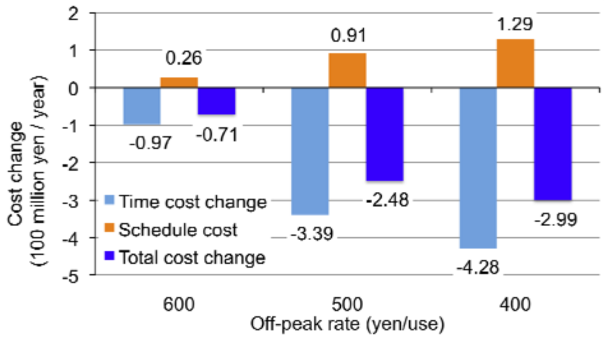

Figure 9. Changes in total cost reduction (100 million yen / year) for each toll discount rate of early morning discount

c) Benefit

Benefit is defined as the difference in total travel costs between the normal toll charges and discounted toll charges. Travel cost as social cost includes time cost and schedule cost but does not include toll.

As illustrated in Figure 9 setting the early morning hour toll discount to 400 yen would lead to a total benefit estimated at 299 million yen per year.

7.2. Assessing the traffic improvement effects of toll discounting during daytime off-peak hours

7.2.1. Discount hours and discount rate. Considering that a traffic jam is momentarily dismissed at 11am hour on the Metropolitan Express Route 3 east bound, the discount hours was set 11am. As for the discount rate, which is currently set 700 yen, three scenarios are calculated; 1) 600 yen, 2) 500 yen and 3) 400 yen.

7.2.2. Result. An analysis using the model described above targeted from 10am to 12pm found the following results.

a) Traffic shift

The traffic shift from 10am hour to 11am hour was 1) 0.04%, 2) 1.7%, and 3) 6.0% for each scenario. 10-minute changes in traffic volume for each toll discount rate are indicated in the Figure 10.

b) Congestion mitigation

A congestion mitigation effect was found at 10am and earlier hour through the traffic shift to late hours. The travel time before 11 am went shorter, however this time reduction did not continue in subsequent time slots as illustrated in Figure 11. So, the yearly total time reduction by daytime toll discount was smaller than by early morning discount (compare Figure 12 to Figure 8).

c) Benefit

The benefit, as defined as the difference between total travel costs of the current rate and discount rate, is the highest when the discount rate is 400 yen, producing estimated 66 million yen per year as shown in Figure 13.

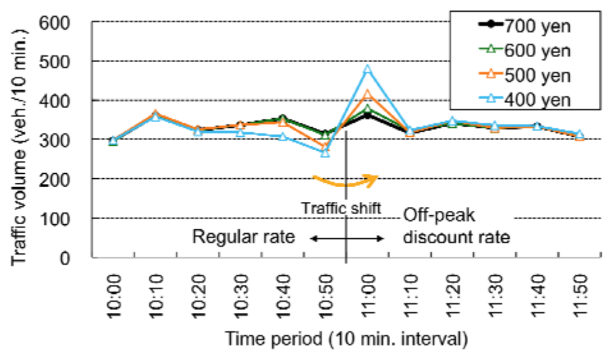

Figure 10. 10-minute changes in traffic volume for each toll discount rate of daytime discount

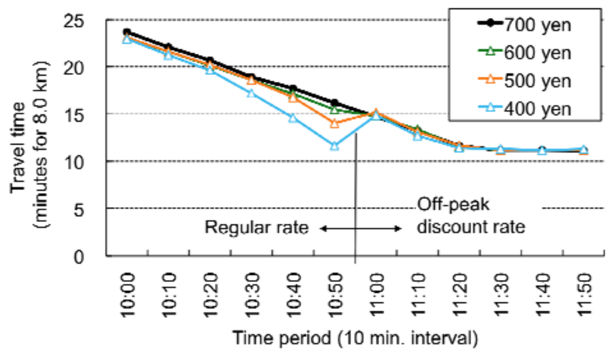

Figure 11. Changes in travel time for each toll discount rate of daytime discount

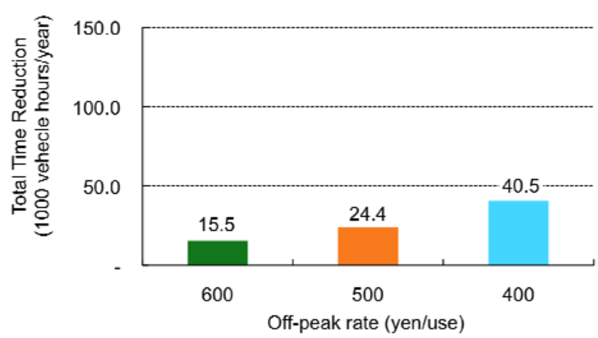

Figure 12. Travel time reduction for each toll discount rate of daytime discount

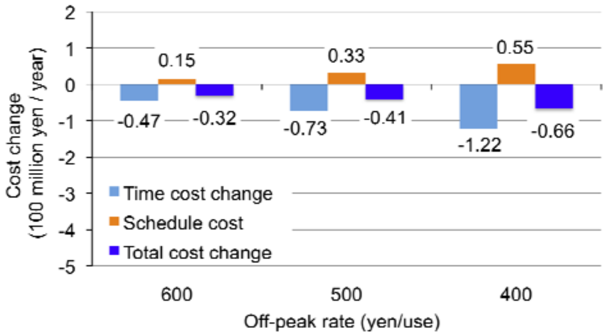

Figure 13. Changes in total benefit (100 million yen / year) for each toll discount rate of daytime discount

7.3. Assessment summary of the traffic improvement effects from increasing the toll discount

Table 3 represents a summary of the assessment results of the three toll scenarios. The results showed that the early morning off-peak toll discount had the greater effect on traffic flow improvement than the daytime off-peak toll discount.

Table 3. Major findings of the traffic flow improvement

Tolling scenarios	Discount Rate	Traffic shift	Benefit (million yen/year)
Early morning off peak hour discount	400 yen/use (-43%)	5.2%	299
Daytime off peak hour discount	400 yen/use (-43%)	6.0%	66

8. Observations

8.1. Relationship between traffic time shifts and congestion mitigation effects

(1) Shifting traffic volume from peak hours of congestion to non-peak hours prior to congestion proved highly effective in mitigating congestion. Vehicles shifting to an earlier time reduce the number of vehicles on the road during later hours, which effectively dissipate traffic jams and other congestion. Therefore, levying broad toll discounts on morning hours prove most effective.

(2) When offering an off-peak toll discount during the daytime hours traffic jams from previous hours were mitigated, but traffic jams in later hours were not mitigated, thus the effect of overall off-peak toll discounting was limited.

8.2. Assessing estimate results of schedule change cost

The schedule change cost was able to be estimated using observed values from traffic volume shifting to toll discount hours as the result of an actual toll discount. Values estimated by Small, et al (1982) [8] using a Stated Preferences Survey showed an early arrival unit cost of 7.5 yen per minute and time delay unit cost of 29.2 yen. Whereas, this study found estimated values similar to these values, including early departure / arrival unit cost of 5.07 yen per minute, late departure benefit 5.07 yen per minute and late arrival cost of 27.5 yen per minute.

However, the meaning of these values differs. The early arrival cost estimated by Small et al (1982) [8] represented the time cost of the period between early arrival and the scheduled time, while the time delay cost represented the time cost of being late to the scheduled time, with each relating to the cost of commuters.

In contrast, values estimated in this study were the time cost of departing prior to the normal departure time and arriving early prior to the normal arrival time, as well as the time cost of departing later than the normal departure time and arriving later than the normal arrival time. All persons do not necessarily have a scheduled time, while driving purposes include a variety of different reasons. As such, the estimated values used in this study are more suitable to analyze the road traffic.

8.2. Assessing simulation results

(1) This study was able to develop a model that obtained endogenously traffic volume changes in response to hourly toll changes by applying the user equilibrium concept to the selection of departure time.

(2) This study was able to estimate the values of early departure and late arrival cost.

(3) This study conducted a simulation using morning hourly-observed traffic data and demonstrated societal benefits would result from toll discounting.

9. Future direction of research

(1) This study hypothesized fixed total demand on a single route. Greatly altering toll charges would create changes in total demand and shift traffic volume from non-toll roads. Therefore, there is a need to expand the model of this study to include demand function and route selection in order to verify these effects quantitatively.

(2) It is preferable to set varying tolls tailored to specific hours of the day to optimize traffic flow.

(3) This study hypothesized that all road users possessed an equal value of time. It is believed that it would be meaningful to expand the model to include several groups of time value to create a more realistic model.

(4) This study hypothesized that multiple schedule unit costs were equal. Essentially, these unit costs are thought to differ, so it is necessary to measure each unit cost.

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