# Influence Analysis of Expressway Toll Discounts

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**Abstract**: As for the expressway toll, deployment of the Electronic Toll Collection (ETC) system enabled setting various toll levels by time of the day. A variety of toll discounts have been applied to tackle with road transport issues and for economic stimulation. For expressways managed by Japan's three expressway companies (NEXCO Central, NEXCO East and NEXCO West), this study performs 1) elucidation of the change in the traffic conditions, user properties, etc. associated with toll discounts by means of traffic data, ETC user data, etc., 2) traffic assignment simulations for the nationwide road network, and 3) grasping of the effects of each toll discount through consumer surplus analysis using the simulation results.

*Keywords*: Expressway, Toll Discounts, Traffic Simulations, Consumer Surplus Analysis

## 1. INTRODUCTION

In Japan, expanded use of the Electronic Toll Collection (ETC) has enabled fine toll pricing for different time slots. Accordingly, there are a wide range of discounts implemented for the purpose of solving traffic issues and as economic measures. It is likely that there are some discounts that require review in terms of the proper manifestation of their intended effects, while other discounts may be exhibiting their anticipated effects. Additionally, there are concerns over the effectiveness of some of the discounts as traffic policies, including the possibility of them resulting in severe traffic congestion and affecting other transportation systems.

In foreign countries, the introduction of distance-based charging systems is carried out for purposes such as resource procurement or environmental improvement. In EU countries, the introduction of new toll charging systems has recently focused on charging heavy goods vehicles (HGV) (European Commission, 2006; European Commission, 2008; European Commission, 2011). These include using GPS to charge HGVs on the Autobahn in Germany (Rothengatter, W. ,2005; C. Erdmenger, C. Hoffmann, K.Frey,M. Lambrecht, W. Wlodarski ,2010), using the vignette method to charge HGVs in the U.K. (Department for Transport, 2009) and using the Electronic Toll Service to charge HGVs in France (O. Quoy, B. Jacob , 2010). Meanwhile, in the United States, amendments to federal law were proposed in 2014 that would enable charging tolls on existing Interstate Highways that have undergone improvement. In particular, Oregon established a state law in July 2013 to introduce a system by 2015 that will allow payment of distance-based tolls as a replacement for the state gasoline tax (Oregon DOT, 2007). In addition, a variety of pricing policies have been carried out in foreign countries, such as road pricing in London and Singapore, and these efforts have been

the subject of many research papers as well (Y. Tsukada, Daisuke Fukuda, 2013).
Under such circumstances, for expressways managed by Japan's three expressway companies (NEXCO Central, NEXCO East and NEXCO West), the present study performs 1) elucidation of the change in the traffic conditions, user properties, etc. associated with toll discounts by means of traffic data, ETC user data, etc.. But analysis for all expressways and ordinary roads of the nationwide is not able to be evaluated and apply because the observed data such as traffic data or ETC data contain only for a specific road route and section. Therefore, we carried out 2) traffic assignment simulations for the nationwide road network. In addition, to evaluate influence of the toll discount from an economic viewpoint, this study performs 3) grasping of the effects of each toll discount through consumer surplus analysis using the simulation results of with and without the toll discount.
In Europe and America, various pricing such as the charging systems of the expressway has been carried out as new financial resources for toll-free expressways. On the other hand, in Japan, toll road system has been introduced at the first stage of the expressway development. However, in recent years a policy called the toll discount is carried out from a viewpoint of using expressway more effectively. Only Japan employs the expressway toll policy with such a discount all over the world. This study analyzed Japanese special pricing called the expressway toll discount and, through simulation, it also observed economical influence of the toll discount on nationwide road network.

## 2. HISTORY OF HIGHWAY TOLL DISCOUNTS

In the past, Japan's highway toll discounts focused on advance payment discounts such as Highway Card and separate payment discounts targeting heavy users, and there were no specific policies implemented to change the toll depending on the traffic conditions. Implementation of time discounts started with implementation of commuter discounts and late night discounts that were introduced as a result of privatization of the four highway public corporations, managerial efforts by new companies including implementation of new direct control methods and cost reduction, and the decision on introducing various discount schemes through utilization of ETC etc. Later, some limited-time discounts such as "Holiday Max 1,000 Yen" and "Weekday Daytime 30% Discount" were implemented in accordance with the implementation of various discounts associated with the alleviation of debt burden through the partial acceptance of highway debt by the Japanese government as part of economic measures (Expressway Convenience Promotion Project). The "Holiday Max 1,000 Yen" was then discontinued to cope with the aftermath of the Great East Japan Earthquake.
The history of time discounts for standard-size and smaller vehicles on expressways managed by the three NEXCO companies in non-metropolitan areas is shown in Fig.-1, and the history of discounts for mid-sized and larger vehicles on expressways in non-metropolitan areas as well as discounts in metropolitan areas is shown in Fig.-2. Discounts are applied to many time slots as a result of expanded discount schemes. In particular, for standard-size and smaller vehicles on expressways in non-metropolitan areas discounts with different purposes are applied across all time slots, and the toll differences among time slots have become smaller compared to the toll differences that were observed when the time discounts were first implemented.
While there are various additional expressway toll discounts currently implemented including discounts for individual contractors (e.g., mileage discount, heavy use high frequency discount, disability discount) and discounts for specific routes or sections, the present study carries out analysis on area-wide time discounts implemented for metropolitan and non-metropolitan areas.

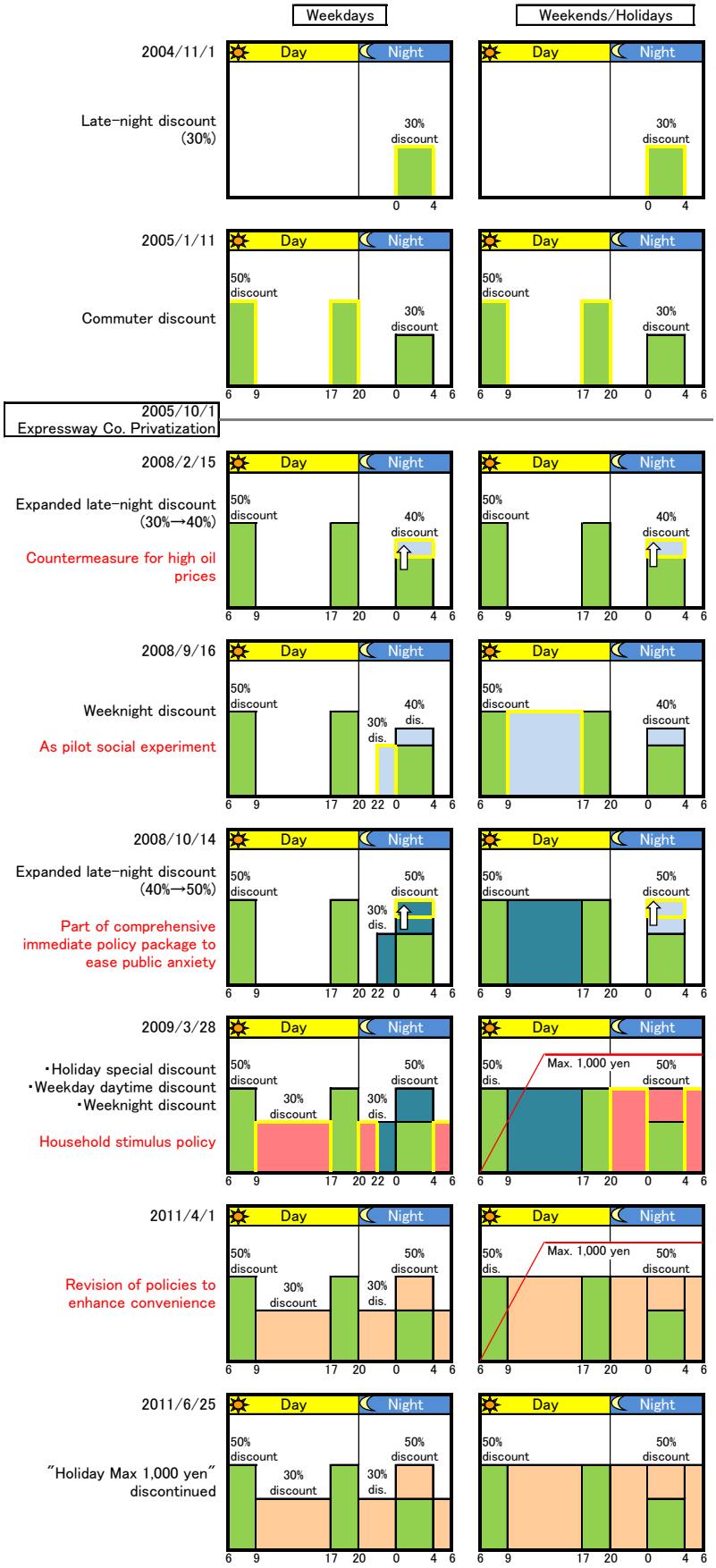


Fig.-1 History of time discounts for non-metropolitan areas (standard-size and smaller vehicles)

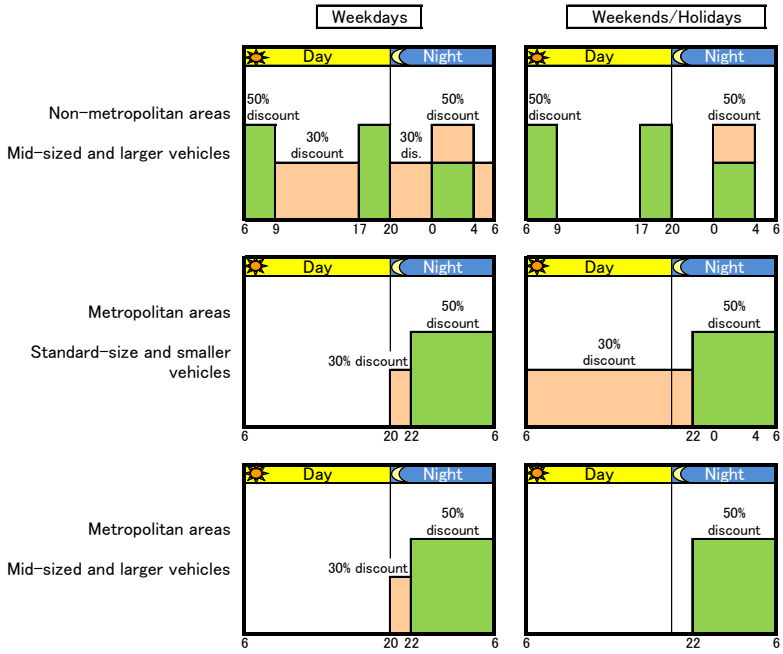


Fig.-2 Current time discounts
(non-metropolitan areas for mid-sized and larger vehicles and metropolitan areas)

## 3. INFLUENCE ANALYSIS OF EXPRESSWAY TOLL DISCOUNTS BASED ON OBSERVATIONAL DATA

The implementation purpose of expressway toll discounts has been changed in response to the expanded use of ETC and social and economic situations. In this section, influence analysis is carried out for four different time discounts by comparing observed traffic data etc. before and after the implementation of discounts. The discounts analyzed were “late night discount”, “commuter discount”, “weekday 30% discount” and “holiday 50% discount”, and the analysis was carried out taking into account the implementation purpose of the expressway toll discounts.

While in principle the analysis is carried out through year-on-year comparisons for individual implementation in order to analyze the effect of the implementation, in some cases the analysis is carried out for other comparison methods from the viewpoint of eliminating the effects of other discounts etc.

### 3.1 Commuter Discount

The trend of reduced traffic at parallel ordinary roads and increased traffic at expressways was identified for the implementation of commuter discount, while the degree of change in the expressway traffic varied depending on the route. Regarding the traffic by time slot, there is a trend of having a large increase rate in expressway traffic during reduced-toll hours (Fig.-3).

Analysis using the traffic congestion data identified the effect of the discount on alleviating traffic congestion at parallel ordinary roads for approximately half of the sections. The degree of such a trend varied depending on the area or route, and the amount of traffic congestion increased for expressways.

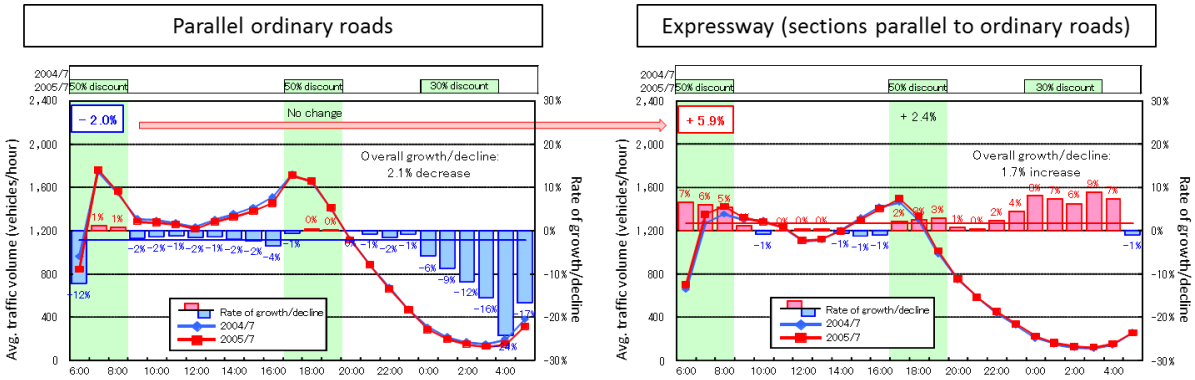


Fig.-3 Change in the spot traffic volume before and after implementation of commuter discounts

## 3.2 Late Night Discount

The trend of reduced traffic at parallel ordinary roads and increased traffic at expressways was identified for the implementation of late night discount, centering on freight vehicles (Fig.-4). No increase in the amount of traffic congestion on expressways during the reduced-toll hours was observed. Meanwhile, regarding the expansion of the discount rate to 40% and 50%, no further migration of traffic from parallel ordinary roads to expressways was identified.

Therefore, it can be said that although this discount has an effect to induce users to take travel behavior that contributes to an effective use of highways, the expansion of the discount rate is not manifesting its intended effects.

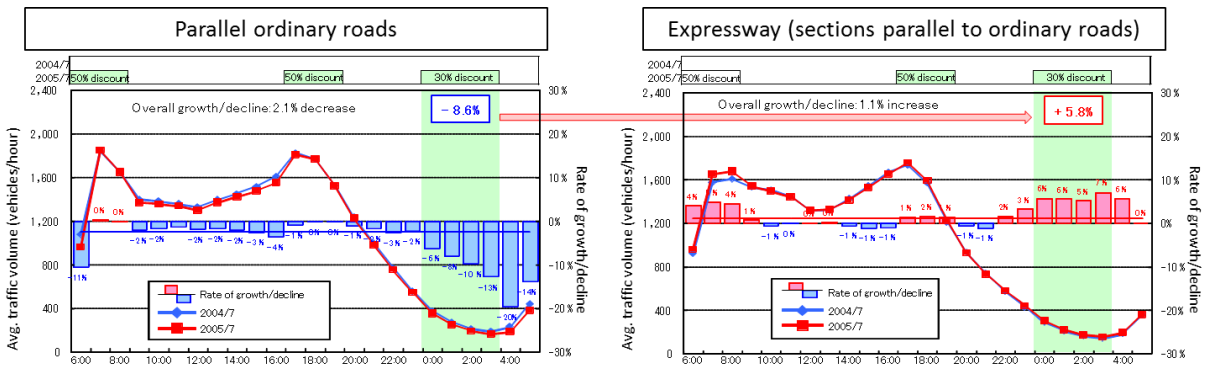


Fig.-4 Change in the spot traffic volume before and after implementation of late night discounts

## 3.3 Weekday 30% Discount

For the weekday 30% discount, a certain level of traffic migration from ordinary roads to expressways was observed for car types of mid-sized and larger, for both daytime and nighttime, and for the sections with approximately 30-40% discounts. Meanwhile, no clear effects were identified for car types of standard-size and smaller, for either daytime or nighttime.

### 3.4 Holiday 50% Discount (30% Discount for Metropolitan Areas)

Analysis using the traffic congestion data identified that the number of traffic congestion incidents on holidays increased after implementation of the holiday 50% discount. Analysis using the ETC user data clearly indicated an increase in the traffic volume on long-distance sections (Fig.-5).

Meanwhile, regarding the effect on tourism activities, although analysis using the tourist volume data showed that there were some suburban prefectures in the Kanto area (e.g. Ibaraki, Tochigi, Chiba) that received an increased number of visitors, the analysis could not clearly identify the quantitative effects of the discount on increased tourism demands (Fig.-6). Effects of the discount on the tourism activities may require further studies since the period of discount implementation coincided with other incidents that may also have affected tourism activities, including the economic downturn precipitated by the Lehman Brothers bankruptcy and changes in retail prices of gasoline.

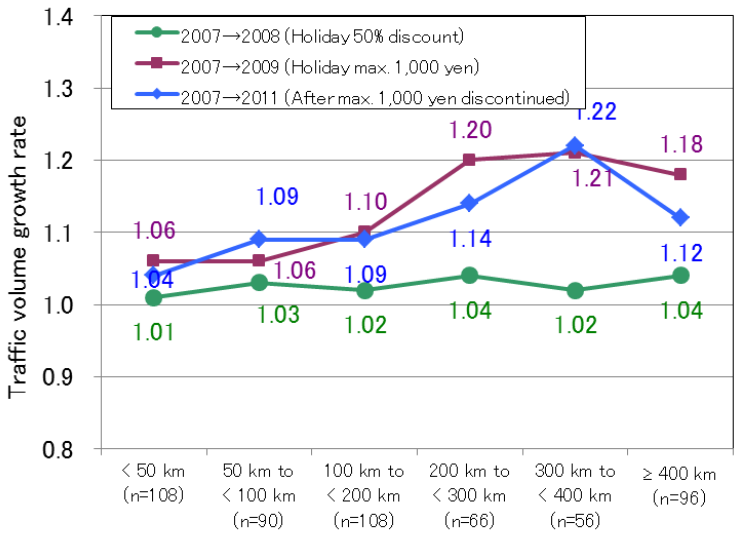


Fig.-5 Change of traffic from the three metropolitan areas to all interchanges in Japan

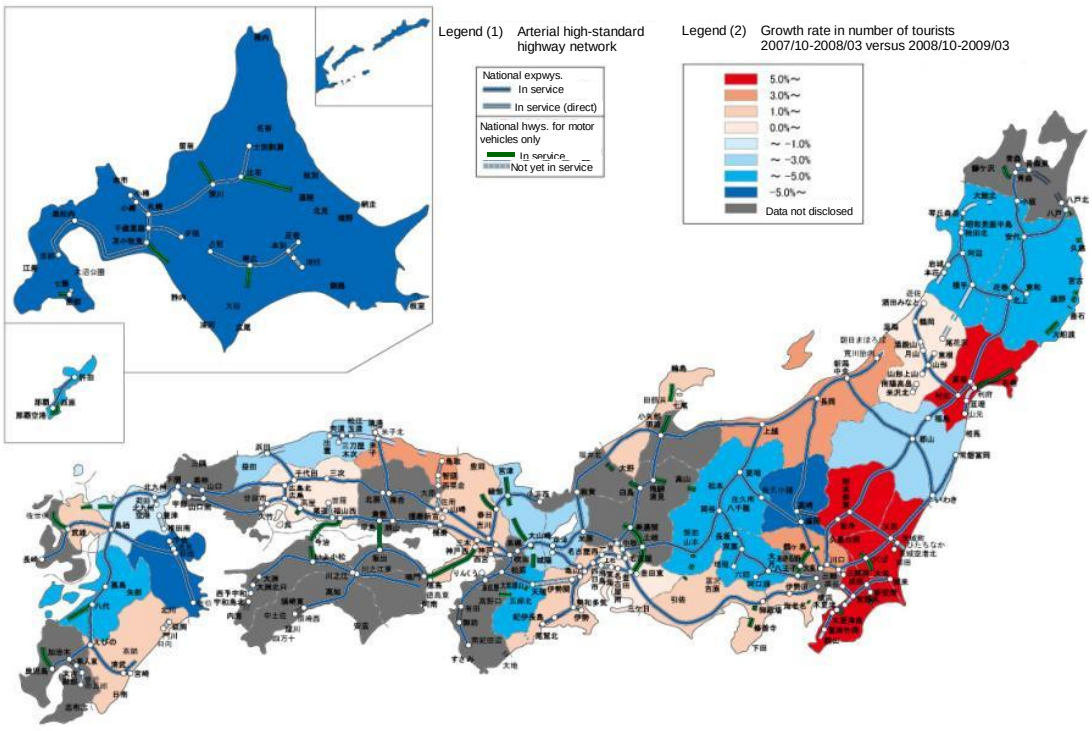


Fig.-6 Growth rate in the number of tourists by prefecture
(comparison between the period from Oct 2007 to Mar 2008 and the period from Oct 2008 to Mar 2009)

## 4. TRAFFIC ASSIGNMENT SIMULATION

The aforementioned influence analysis of expressway toll discount based on observational data does not provide data for unobserved highways or ordinary roads. Therefore, this study carries out simulations with and without toll discount using a traffic volume estimation model for the nationwide arterial highway network and analyzes the effects of discounts based on the traffic volume at all the arterial highways in Japan including expressways.

### 4.1 Outline of Nationwide Traffic Assignment Model

The nationwide traffic assignment model is calculated by the OD (origin-destination) table for the nationwide arterial highway network (number of links: 1,216,149, number of nodes: 858,605) and zones (number of zones: 6,795). The model structure applies incremental assignment by the OD division in consideration of the processing time in the large-scale network. In incremental assignment in the route choice model of the expressway and ordinary road, logit model by the variables of travel time and toll amount is applied. In the travel time required to be used for the route choice of the expressway and ordinary road, a route of the shortest time required every OD division is chosen. Described below are the time-dependent OD table used in the model as well as the targeted reduced-toll hours and their respective toll discount rates. As for the road user, the departure time or the inflow time of the expressway would be influenced depending on the rate discount. However, the OD table by the toll discount shall not change because these behavior changes were not grasped in the analysis with observed data.

#### 4.1.1 Formulation of time-dependent OD tables that match the time discounts

In order to analyze the effects of time discounts, the time slots are expressed by subdividing the daily OD traffic volume into the OD traffic volume for individual time slots of reduced-toll hours. In the automobile OD survey of the road traffic census automobile OD survey that becomes the base of OD traffic volume, the departure time of the trip origin and the arrival time at the destination are surveyed. In the present study, the OD traffic volume was categorized into each time slot using the departure time of the trip origin, and the OD tables that match the individual time discounts are formulated.

### 4.1.2 Target reduced-toll hours and discount rates

In order to evaluate the effects of expressway toll discounts in 2010, the time slots investigated in this study were designated to be 7 categories as shown in Table-1 in accordance with the time discounts that were in place in 2010. The OD traffic volume data used for traffic volume estimation are for weekdays only. The discount rates at individual time categories are separately specified for metropolitan and non-metropolitan areas, as shown in Table-1.

Table-1 Time Slot Category and Toll Discount

| Time category | Time slot | Non-metropolitan areas | Metropolitan areas |
|---|---|---|---|
| (1) Morning commute | 6:00-9:00 | Commuter discount (50% off) | |
| (2) Daytime | 9:00-17:00 | Weekday daytime discount (30% off) | |
| (3) Evening commute | 17:00-20:00 | Commuter discount (50% off) | |
| (4) Nighttime (1) | 20:00-22:00 | Weekday nighttime discount (30% off) | Nighttime discount (30% off) |
| (5) Nighttime (2) | 22:00-24:00 | Weekday nighttime discount (30% off) | Nighttime discount (50% off) |
| (6) Late night | 0:00-4:00 | Late night discount (50% off) | Late night discount (50% off) |
| (7) Early morning | 4:00-6:00 | Early morning discount (30% off) | Early morning discount (30% off) |

### 4.2 Comparison of Estimated Traffic Volume and Actual Traffic Volume

The results of comparisons between the traffic assignment results and actual traffic volume on the main expressways are shown below. While the model is generally validated for each time slot, the estimated traffic volume was underestimated compared to the actual traffic volume for the early morning (Fig.-8) and nighttime (Fig.-12, Fig.-13) where the OD traffic volume is small.

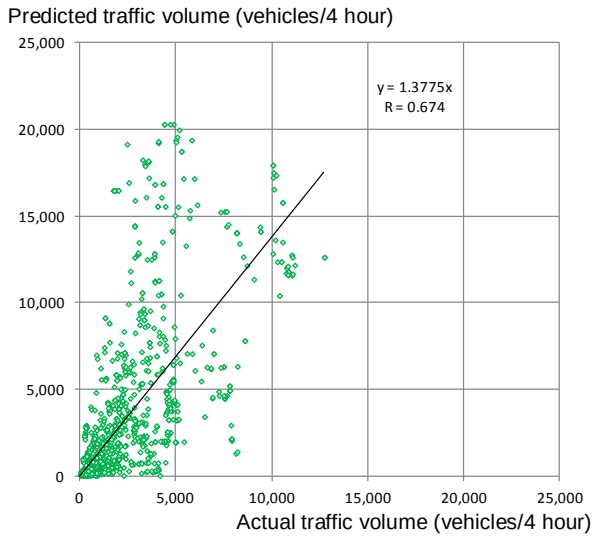


Fig.-7 Traffic volume estimation result and actual traffic volume (late night, 0:00-4:00)

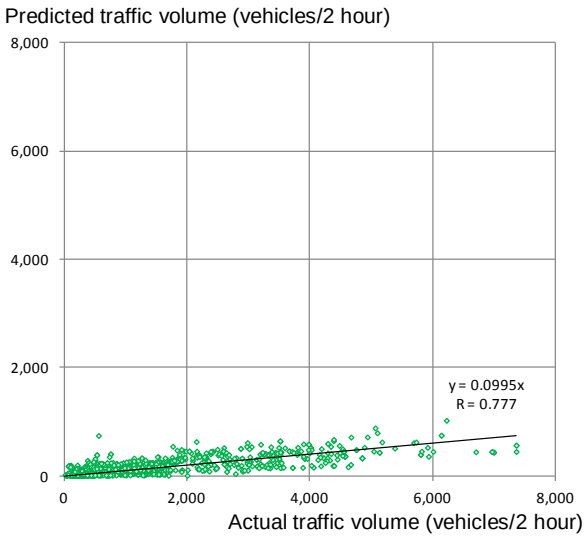


Fig.-8 Traffic volume estimation result and actual traffic volume (early morning, 4:00-6:00)

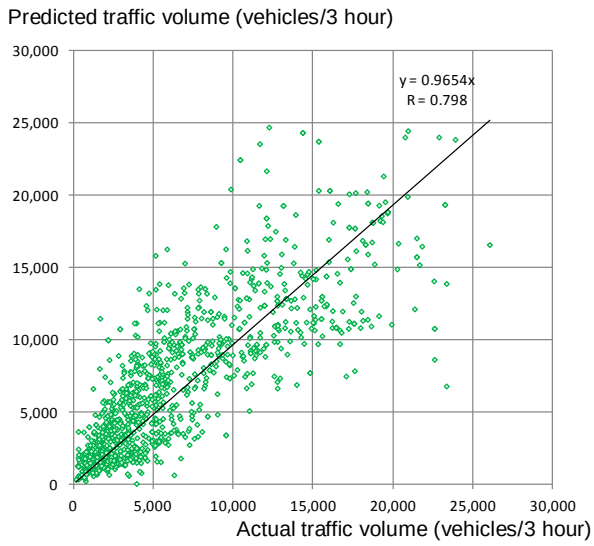


Fig.-9 Traffic volume estimation result and actual traffic volume (morning commute, 6:00-9:00)

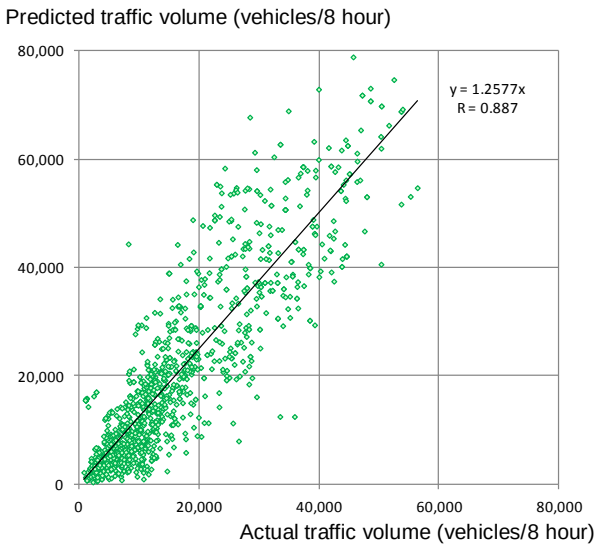


Fig.-10 Traffic volume estimation result and actual traffic volume (daytime, 9:00-17:00)

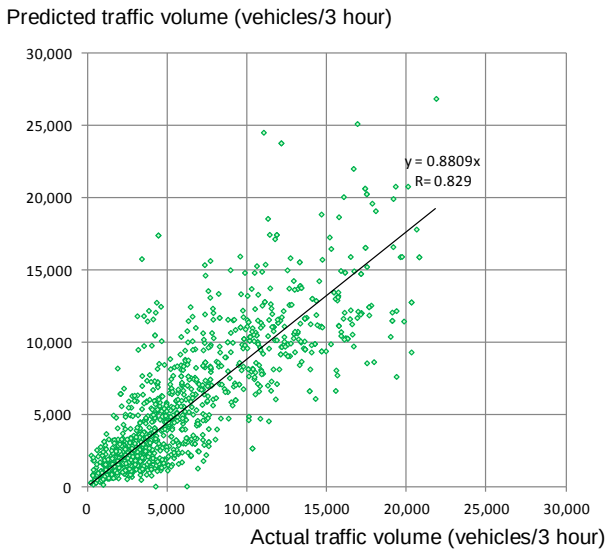


Fig.-11 Traffic volume estimation result and actual traffic volume (evening commute, 17:00-20:00)

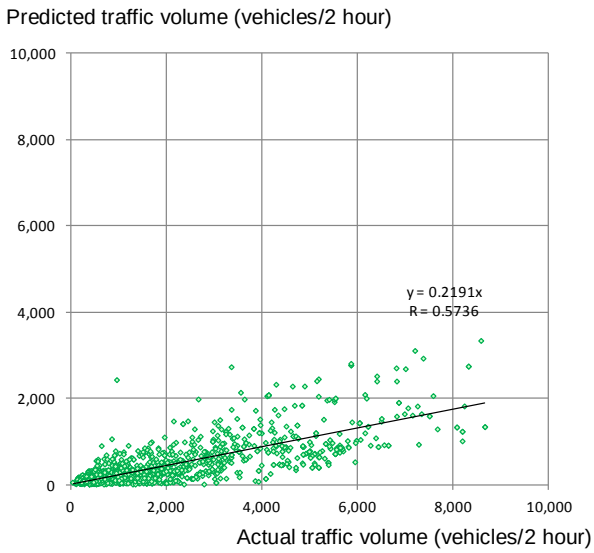


Fig.-12 Traffic volume estimation result and actual traffic volume (nighttime (1), 20:00-22:00)

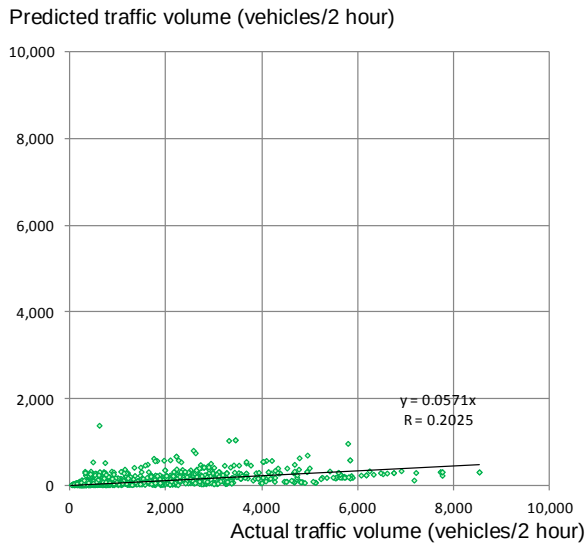


Fig.-13 Traffic volume estimation result and actual traffic volume (nighttime (2), 22:00-24:00)

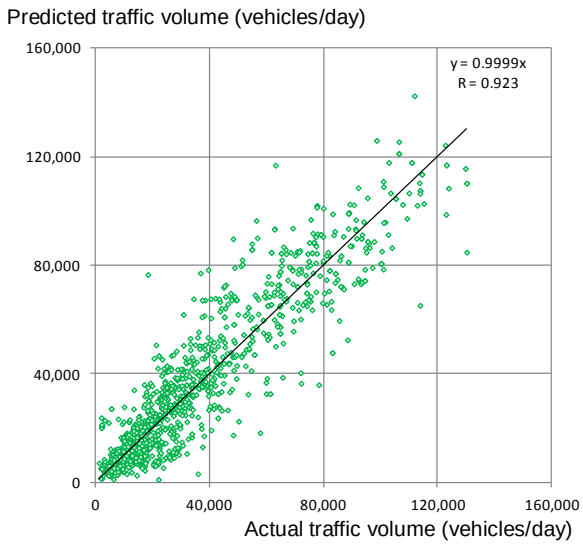


Fig.-14 Traffic volume estimation result and actual traffic volume (daily total)

### 4.3 Results of traffic assignment simulation

Using the nationwide traffic volume estimation model, simulations were carried out for cases with and without time discounts.

As an example of simulation results, the rate of change in the traffic volume with and without toll discounts for all expressways in Japan (morning commute 6:00-9:00) is shown in Fig.-15. This simulation is about a change in the shift from an ordinary road to the expressway, and there would not be the induced traffic by the toll discount.

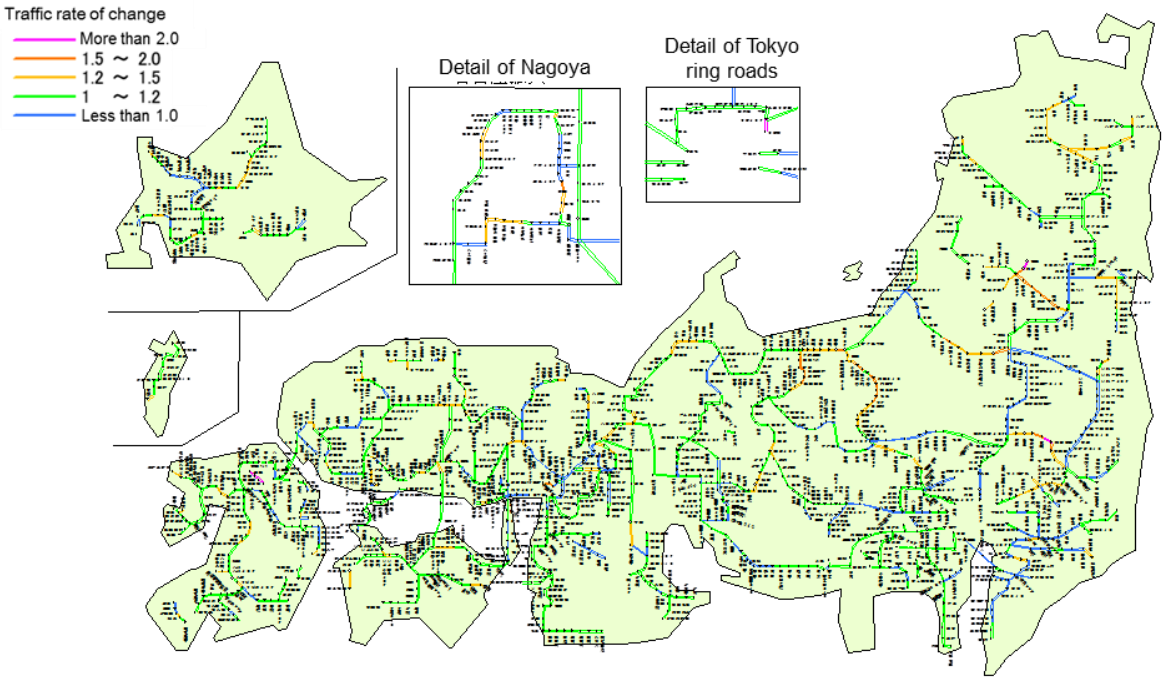


Fig.-15 Rate of change in the traffic volume with and without toll discount (morning commute 6:00-9:00)

The average traffic volumes derived from the nationwide traffic assignment simulation results are shown in Fig.-16 to Fig.-23. For all time slots implementation of toll discounts induced an increase in the traffic volume on expressways and a decrease on ordinary roads, indicating a similar trend with the aforementioned transition in the actual traffic volume based on observational data. However, the results for the early morning and nighttime periods indicated that average traffic volumes in these time slots are smaller than in other time slots, and in addition are roughly the same for expressways and ordinary roads. The results indicated the possible improper representation of traffic assignment between expressways and ordinary roads for time slots with smaller OD traffic volumes (i.e. early morning and nighttime) compared to other time slots.

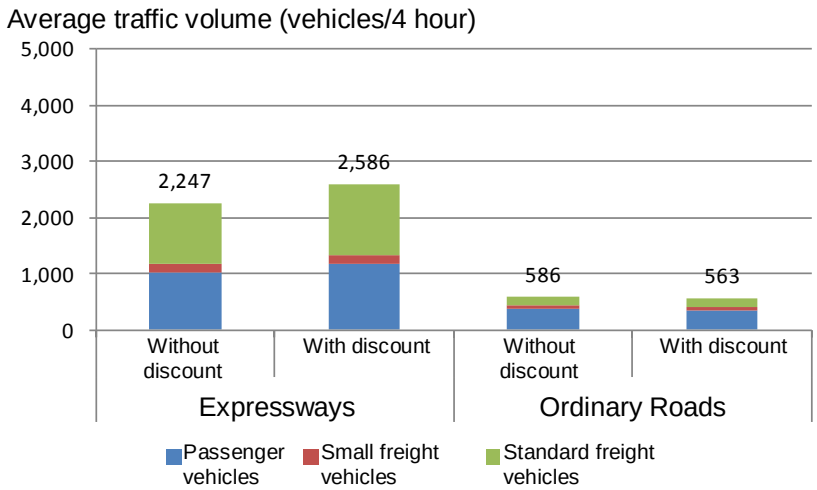


Fig.-16 Average traffic volume for expressways and ordinary roads by time and by vehicle type (late night 0:00-4:00)

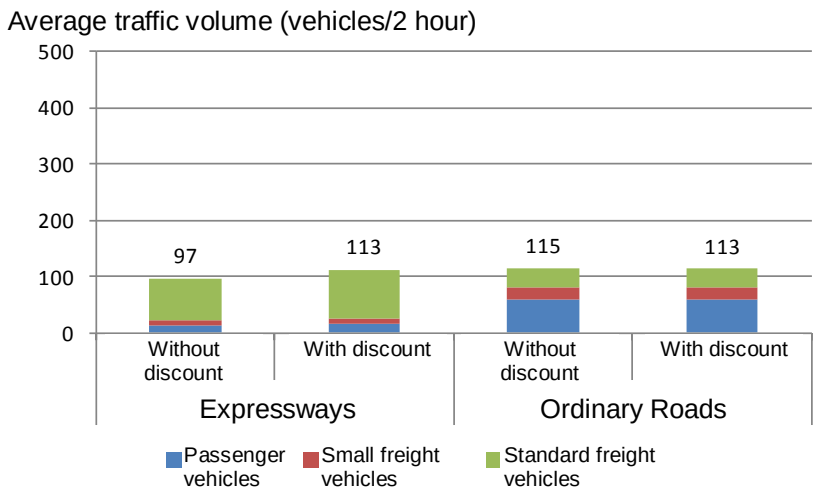


Fig.-17 Average traffic volume for expressways and ordinary roads by time and by vehicle type (early morning 4:00-6:00)

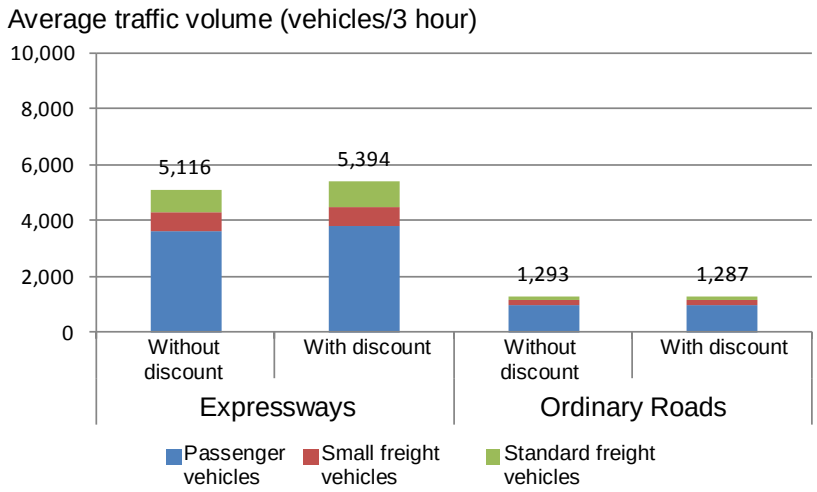


Fig.-18 Average traffic volume for expressways and ordinary roads by time and by vehicle type (morning commute 6:00-9:00)

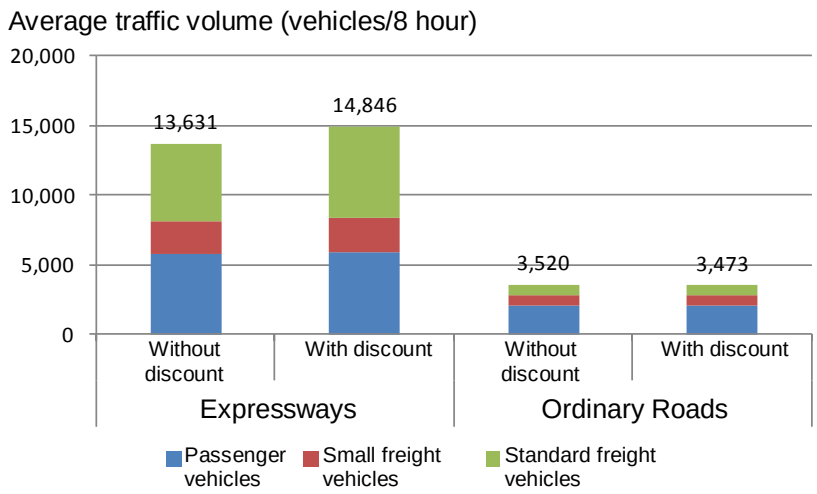


Fig.-19 Average traffic volume for expressways and ordinary roads by time and by vehicle type (daytime 9:00-17:00)

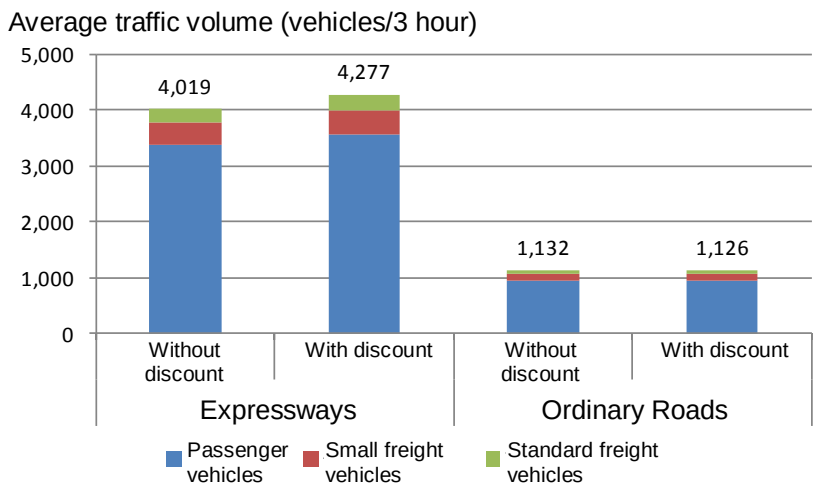


Fig.-20 Average traffic volume for expressways and ordinary roads by time and by vehicle type (evening commute 17:00-20:00)

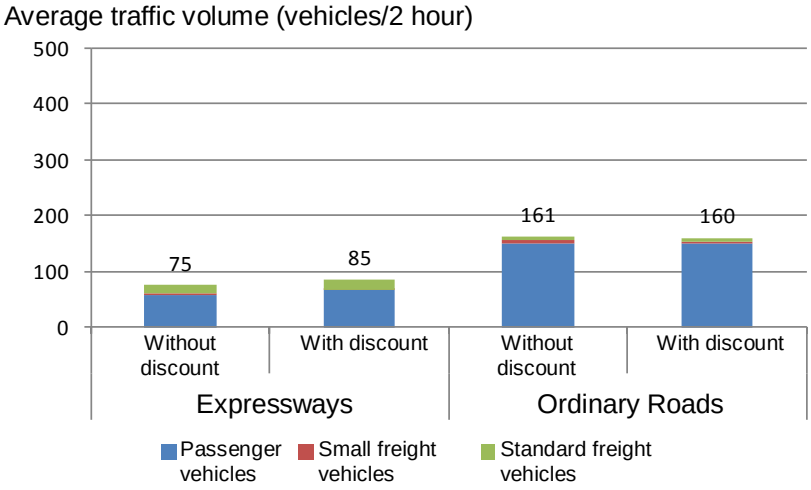


Fig.-21 Average traffic volume for expressways and ordinary roads by time and by vehicle type (nighttime (1) 20:00-22:00)

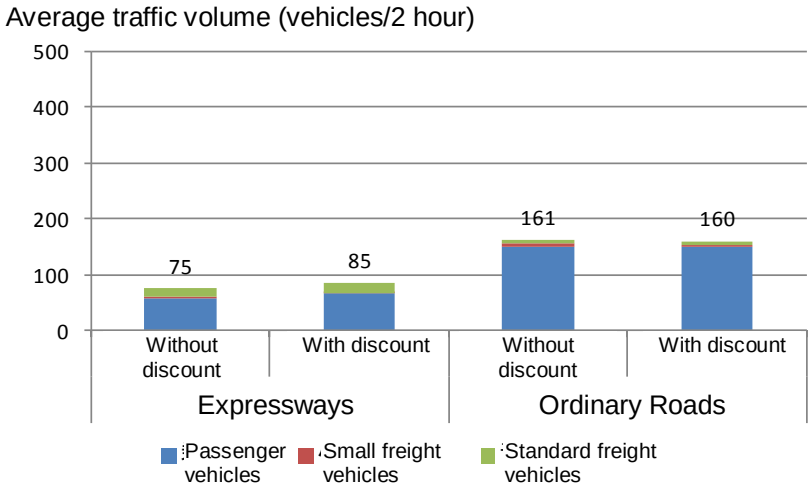


Fig.-22 Average traffic volume for expressways and ordinary roads by time and by vehicle type (nighttime (2) 22:00-24:00)

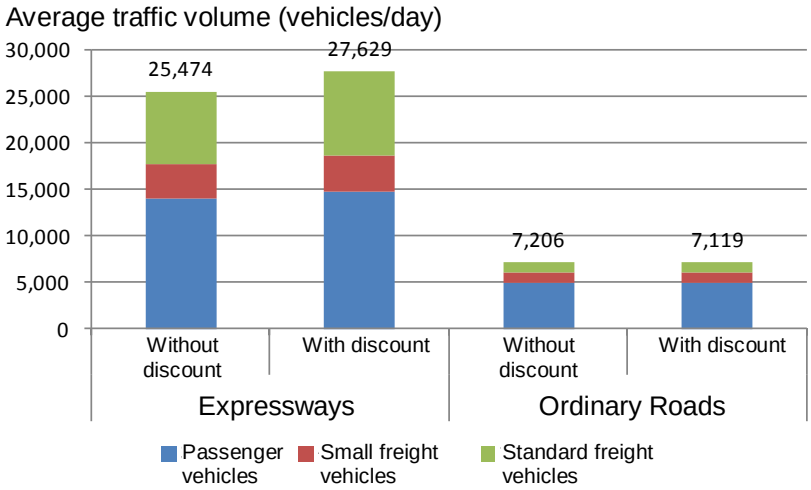


Fig.-23 Average traffic volume for expressways and ordinary roads by time and by vehicle type (daily total)

## 5. Influence analysis of each toll discount through consumer surplus analysis using the simulation results

Benefits of expressway toll discounts are measured using the nationwide traffic assignment simulation results.

### 5.1 Application Concept of Consumer Surplus Analysis

For the measurement, the traditional "consumer surplus approach" method is applied since user benefits constitute the majority of the social benefits. Benefit measurement using the consumer surplus approach is carried out using Marshall's consumer surplus that is expressed as the area to the left hand side of demand curves (H. Morisugi, T. Kohno, Y. Ohmura,2009; Varian, Hal R. ,2005; Y. Kanemot, K. Hasuike, T. Fujiwara, 2006). Here, the benefit to consumers (road users) arising from expressway toll discounts is calculated as the difference between the consumer surplus with and without toll discounts. The benefit, B, is derived from the trapezoidal rule as:

$$B = \frac{1}{2}\left(Q\left(GP^{wo}\right) + Q\left(GP^{w}\right)\right)\left(GP^{wo} - GP^{w}\right) \tag{1}$$

where,

$B$ : benefit

$GP^{wo}$ : generalized cost without toll discounts ,

$GP^{w}$ : generalized cost with toll discounts,

$Q\left(GP^{wo}\right)$: traffic volume for $GP^{wo}$ , and

$Q\left(GP^{w}\right)$ : traffic volume for $GP^{w}$

The benefit of toll discounts using the consumer surplus approach is measured from the social surplus (summation of consumer surplus, producer surplus and government revenue) that is shown in Fig.-24. The social benefit is measured by measuring the social surplus with toll discounts and that without toll discounts.

The consumer surplus is calculated from the generalized cost based on the traffic volume, travel time and expressway tolls obtained by the nationwide traffic assignment simulation. The producer surplus is the income of expressway companies from the tolls, which is calculated from the traffic volume obtained by the nationwide traffic assignment simulation. The government revenue is the income from the fuel tax, which is calculated from the fuel efficiency and fuel tax rates based on the use distances obtained by the nationwide traffic assignment simulation. As shown in Fig.-24, implementation of expressway toll discounts is expected to induce a decrease in the generalized cost and an increase in the consumer surplus of road users, if there is no new traffic congestion occurring on expressways. Additionally, the producer surplus (income of expressway companies from the tolls) is expected to decrease due to the implementation of expressway toll discounts as long as there is no significant increase in the overall expressway traffic volume. Meanwhile, the government revenue (income from the fuel tax) is expected to increase due to an increase in the expressway traffic volume, an increase in the overall trip distance, and thus an increase in fuel consumption.

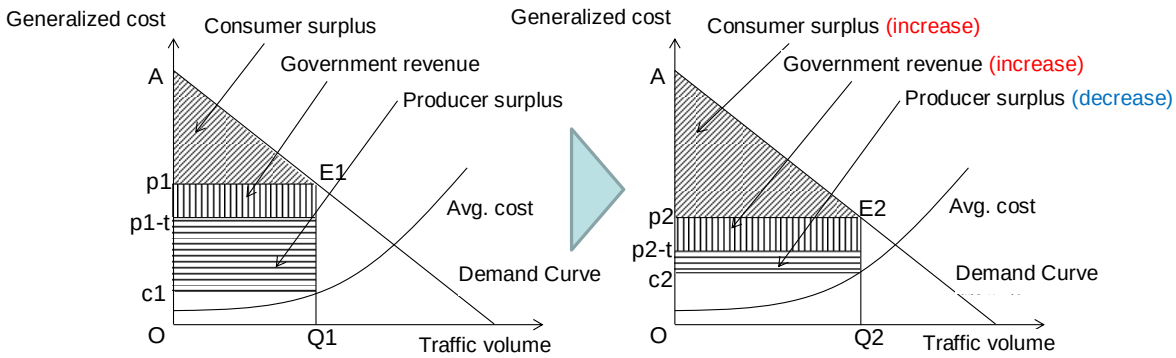


Fig.-24 Schematic illustration of social surplus estimation using the consumer surplus approach

## 5.2 Measurement of Social Benefits Based on Consumer Surplus Approach

The measurement results of social benefits based on the consumer surplus approach are shown in Fig.-25 and Fig.-26. As mentioned previously, the implementation of expressway toll discounts resulted in an increase in the social surplus due to an increase in the consumer surplus of road users, a decrease in the producer surplus (income of expressway companies from the tolls), and an increase in the government revenue (income from the fuel tax). However, while implementation of expressway toll discounts resulted in a significant increase in the consumer surplus of road users, the degree of decrease in the producer surplus was half or more of the degree of increase in the consumer surplus. Additionally, while the government revenue increases, the degree of increase was relatively small.

The measured social benefits by time slot was the largest for the daytime period (9:00-17:00) with approximately 231.3 billion yen per year where the discount duration is long and the traffic volume is large, followed by the late night period (0:00-4:00) with approximately 36.7 billion yen per year, the evening commute period (17:00-20:00) with approximately 27.0 billion yen per year, and by the morning commute period (6:00-9:00) with approximately 16.2 billion yen per year. The social benefits in the early morning and nighttime discount periods were extremely small, as mentioned above, due to the small traffic volume.

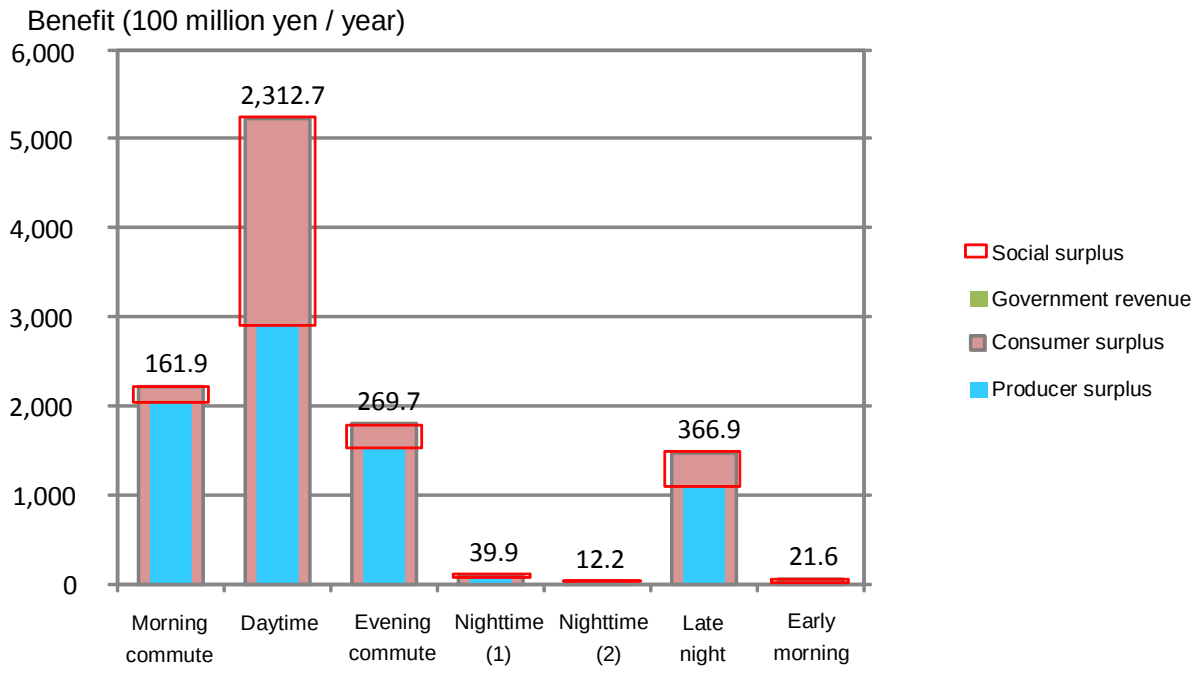


Fig.-25 Measurement results of social benefits

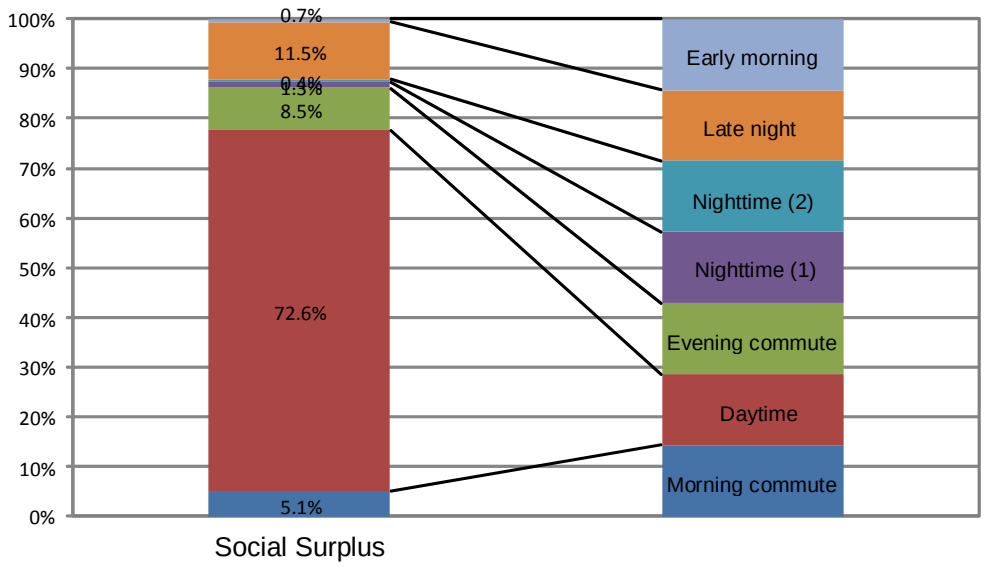


Fig.-26 Social benefit ratio by time slot

### 5.2.1 Commuter discounts, late night discounts

Among toll discounts implemented at the time of privatization, the commuter discounts were identified to have an effect on alleviating traffic congestion at approximately half the sections of ordinary roads, while the degree of effect varied depending on the section. However, although the scheme was implemented assuming application to commuters, the toll discount is applied to all vehicles that travel expressways during the commuting time period. For that reason, while the basic concept of commuter discounts is to maintain the policy purpose, review of the discount contents and methods (e.g. target, day) may be required in order to maximize their effects.

For the late night discount, the 30% discount implemented at the time of privatization appears to have had some effect on the improvement of the roadside environment due to migration of traffic from parallel ordinary roads to expressways. However, the expansion of the discount rates to 40% or 50% did not induce further migration of traffic from parallel ordinary roads to expressways. Therefore, the basic concept of late night discounts should be to maintain the 30% discount, while the expanded discounts may have to be reviewed after gaining a clearer picture of their effects.

### 5.2.2 Weekday 30% discount, holiday 50% discount (30% discount for metropolitan areas)

Regarding the weekday 30% discount that was implemented as part of the convenience promotion project, no specific migration of traffic from parallel ordinary roads to expressways was observed for the sections, other than those with approximately 30-40% discounts, even for vehicle types of mid-sized and larger. It may be required to review the discount contents after gaining a clearer picture of their effects.

Regarding the holiday 50% discount (30% discount for metropolitan areas), while some effects on local revitalization were identified, an increase in the amount of traffic congestion on expressways was also observed. Therefore, it may be required to consider in the future experimenting with reduced discount rates or other measures while potentially continuing toll discounts in non-metropolitan areas where traffic congestion does not become notable.

## 6. Summary

Considering opinions stating that the toll discounts are not fully exhibiting the effects anticipated at their implementation because they are not recognized or perceived by the users due to the confusion regarding the regular prices arising from the existence of various toll discounts, future toll discounts may have to be limited to simplified discounts that can induce change in the behavior of users.

Additionally, concurrent implementation of various discounts with difference purposes is causing a reduction in their effects compared to their anticipated effects, for all discount schemes. Examples include discounts for all time slots on weekdays at a rate of 30% or more, and expansion of late night discounts nullifying the toll booth congestion alleviation effect of the weekday 30% discount. It is necessary to review toll discounts from the viewpoint of proper manifestation of the toll discounts intended effects.

The present study evaluated the effect of expressway toll discounts on the change in travel behavior using traffic data. As a result, while a certain level of change in travel behavior was identified associated with implementation of toll discounts, it was indicated that the degree of change varies depending on the type of discount, area, and route. Additionally, some discounts were identified to have negative impacts (e.g. worsened traffic congestion) or no specific effect. The present study identified the possible necessity of reviewing the discount contents and method depending on the toll discount scheme.

Future studies may include further detailed analysis of behavioral change of users and identification of discount contents and methods that induce behavioral change of users.

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