Comprehensive Analysis of Toll Price Elasticity of Demand for Toll Roads - Demonstration Projects on Flexible Charge in Japan -

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Abstract: In Japan, the implementation of policies designed to reduce traffic congestion in ordinary roads by providing discounted toll road charges, and thereby the shift of traffic from ordinary roads to toll roads, became more practical with increased utilization of the electronic toll collection (ETC) system. We analyze toll price elasticity of traffic demand, which were directly measured through these nationwide demonstration projects, as the main indicator, to (a) compare various conditions, and (b) perform a regression analysis of toll price elasticity for interchange (IC) pairs, in order to identify the determinants of elasticity and to explore the most suitable conditions for a detailed toll pricing policy using ETC. In addition to vehicle type, discount rate, and difference in time frame, these analyses also consider geographical conditions of toll roads, such as the distance from an ordinary road to an IC, as factors affecting toll price elasticity of demand.

Keywords: Toll Road, Discounted Charge, Toll Price Elasticity, Regression Analysis, Electronic Toll Collection

1. INTRODUCTION

As a result of financial challenges and limited land availability, there is increasing demand in Europe, Asia, and the United States for an effective transportation policy that, within the existing allocated space, could reduce traffic congestion, improve road traffic safety, and conserve the environment. Information Technology (IT) has been actively used in the field of expressway transportation management to collect information and develop policy, including pricing and others intended to strengthen the transport network. Especially desired are effective strategies for reducing urban and regional traffic congestion by controlling traffic, through the collection of charges or the introduction of new road pricing policies. For example, in the United States, a high occupancy toll (HOT) lane pilot program that makes use of electronic tags to reduce traffic congestion, and a distance-based toll pilot project that makes use of the global positioning system (GPS) to secure and procure charges, are being conducted and evaluated in the states of Oregon and Minnesota. In Europe, a distance-based charge for large-sized vehicles, with a charging system that makes use of GPS or dedicated short range communications (DSRC), has been implemented in several countries like Germany. In addition, a congestion tax that utilizes an automatic number plate recognition (ANPR) system has been implemented in London and Stockholm. Although there were many arguments for and against road pricing at the time of its introduction in Stockholm, three years after the permanent implementation of it, urban traffic has decreased by 24%, and citizen attitude supporting for road pricing has increased to 74%.

In Japan, demonstration projects involving toll road charges were conducted in various locations throughout the country mainly in the middle of 2000's, with the principal objective of shifting traffic from ordinary roads to toll roads, thereby improving the regional roadside environment and reducing traffic congestion. Based on the results of these projects, a policy establishing discounts on toll charges collected by ETC has been widely adopted on toll roads.

As discussed above, more countries have begun adopting pricing policies that involve the use of IT; and thus ensuring the acceptance of these policies by users and nearby residents, and being sensitive to privacy concerns, are becoming increasingly important. At the same time, pricing policies must be evaluated in terms of performance-based data to ensure an effective and efficient implementation of the pricing policy.

In light of the foregoing, the objective of this paper is to examine the effectiveness of a diverse and flexible toll pricing policy in Japan. To achieve this objective, toll price elasticity of demand is used as a main indicator to macroscopically understand the overall relationship between changes in toll price and changes in demand. Using regression analysis with the interchange (IC)-level data across the projects conducted in the whole Japan, factors that would affect toll price elasticity of demand are comprehensively examined.

2. PREVIOUS RESEARCH ON PRICE ELASTICITY OF DEMAND FOR EXPRESSWAYS

In terms of research conducted in Japan, Yamauchi (1991) conducted regression analysis to estimate toll price elasticity of demand for the Tomei and Meishin Expressways by each vehicle type. The estimated toll price elasticity was roughly found to be between 0.2 and 0.3, suggesting that ordinary vehicles tended to have higher values than heavy or special vehicles. Tanishita (2005) also performed multiple regression analysis on data regarding expressways and the estimated toll price elasticity was between 0 and 0.4, suggesting that geographical layout, economic circumstances, and road length would affect toll price elasticity of demand. A study by Matsuda and Tsukada (2005) examined toll price elasticity of demand in relation to demonstration projects for a flexible toll charge in Japan. Matas and Raymond (2003) performed multiple regression analysis on data from tolled expressways in Spain and the estimated elasticities were between 0.21 and 0.83. Matas and Raymond (2003) also identified the road length and the level-of-service offered by alternative routes as the influential factors of toll price elasticity of demand.

In terms of studies analyzing the market diffusion impact of ETC on toll price elasticity of demand, there are two relevant ones: Finkelstein (2009) and Ishii and Fukuda (2011). Finkelstein (2009) firstly examined the effects of payment method and the market diffusion rate of ETC. Using multiple regression analysis, she estimated the price elasticity of demand for toll roads in the United States, obtaining a value of approximately -0.06. Finkelstein (2009) also suggested that the interaction between price and the ETC diffusion rate should be taken into consideration and that the toll price elasticity of demand might change gradually diminishes with the increase in the ETC diffusion rate. Ishii and Fukuda (2011) also suggested the possible impact of cashless ETC on the price elasticity of demand of some toll roads in Japan. However, they observed some contradictory trends in this respect.

These previous studies on toll price elasticities of demand obtained by major prior studies are summarized in Table 1.

Table 1. Previous studies of toll price elasticity of demand for toll roads

Author	Expressway	Price Elasticity for demand
Shiraishi (1980)	Tomei Expressway, Meishin Expressway	Car: 0.39～0.59 Large-sized vehicle:0.31～0.59
Yamagami (1991)	All Expressways in Japan	0.36
Takagi et al. (1991)	12 Expressways in Japan	-0.08～1.09
Kajikawa (1999)	Tomei Expressway	0.39
Tanishita (2005)	10 Expressways in Japan	0.04-0.44
Ishi and Fukuda (2011)	30 Expressways in Japan	-(-0.08+0.023 ×ETC*)
Metas et al. (2003)	Expressways in Spain	0.21～0.83
Finkelstein (2009)	Toll Roads in USA	-(-0.061+0.31×ETC*)
Litman (2010)	Toll Bridges, Roads In USA, Canada	-0.04～4.0

Note*: "ETC" denotes the diffusion ratio of ETC adopted vehicles (%)

3. DEFINITION OF TOLL PRICE ELASTICITY OF TRAFFIC DEMAND

Theoretically, the toll price elasticity for travel demand *e* is defined as follows:

$$e = \frac{\partial Q / Q}{\partial p / p} = \frac{p}{Q} \cdot \frac{\partial Q}{\partial p} \tag{1}$$

where *Q* is the quantity demanded and *p* is the toll price.

If observed traffic volumes before and after a change in toll prices are available, the Formula (1) can be rewritten by the following formula:

$$e = \frac{p}{Q} \cdot \frac{\Delta Q}{\Delta p} \tag{2}$$

where ΔQ is the change of traffic volume and Δp is the change of toll price. In this particular study we denote *Q* and *p* as the demand and price before a price change respectively and *Q*' and *p*' as the demand and price after a price change respectively. Then, the toll price elasticity of demand is defined by the following formula:

$$e = \frac{\dfrac{Q' - (Q + Q')/2}{(Q + Q')/2}}{\dfrac{p' - (p + p')/2}{(p + p')/2}} \tag{3}$$

This definition of elasticity is called "arc elasticity" instead of "point elasticity" defined by the Formula (1). Although the toll price elasticity of demand with arc elasticity can be easily calculated using the Formula (3) if both before and after observations are available, changes in economic circumstances, gas prices, and other influential factors are not taken into consideration. Nevertheless, the Formula (3) is considered to be suitable for short-term demonstration projects with toll prices, such as the ones analyzed in this study.

4. OVERVIEW OF THE DEMONSTRATION PROJECTS

In Japan, some "regional problem-solving type" demonstration projects of toll were conducted between 2003 and 2006. Based on unique problems in each region, the objective of the projects was to help shift traffic away from ordinary roads to expressways so as to more effectively utilize the expressways, and to advance measures for reducing traffic congestion, improving the roadside environment, and enhancing road traffic safety. The details of these demonstration projects are described in "Case Studies of Demonstration projects on Toll Road Charges – New Approach to the Utilization of Expressways", 2004 through 2006. The demonstration projects conducted over this three-year period are listed in Table 2.

As shown in Table 2, the demonstration projects were conducted in 75 locations in various metropolitan areas, regional core cities, regional cities, etc. across Japan. Their principal objectives were to decrease early morning and late afternoon traffic congestion (primarily caused by commuters), and to improve the roadside environment by considering traffic associated with logistics and business carried out mainly by large-sized vehicles. The reduction of traffic congestion during the tourist season was an additional objective of some demonstration projects.

5. DATA

In this study, the following variables obtained through the projects were used: locations of individual demonstration projects, toll charges for each vehicle type (car or large-sized vehicle) before and during the demonstration projects, traffic volume between IC pairs, distance between IC pairs and the corresponding toll price elasticity of demand. Unlike many of previous studies that indirectly estimated toll elasticity with econometric model, this study uses the directly measured elasticities with Formula (3). In addition, data on the traffic characteristics of the target expressways and nearby sections of ordinary road were obtained from the Road Traffic Census (2005).

The following information was also taken from the Road Traffic Census: the number of lanes on expressways and ordinary roads corresponding to each target IC pair, average 24-hour traffic volume on weekdays, average driving speed, percentage of large-sized vehicles on the road, degree of congestion, and the total distance to the IC from ordinary roads.

Table 2. Outline of demonstration projects

Purposes	Urban/Rural	Number of Demonstration Project
Reduction of Congestion	Urban Cities	13
Reduction of Noise	Urban Cities	5
Reduction of Congestion	Rural Cities	48
Reduction of Noise	Rural Cities	5
Reduction of Congestion	Tourist Place	4
Total		75

6. FACTORS INFLUENCING TOLL PRICE ELASTICITY OF DEMAND AS SEEN IN THE RESULTS OF THE DEMONSTRATION PROJECTS

6.1 Overview of the Results from the Demonstration Projects

The following phenomena were identified as results of the demonstration projects conducted in each region:

1) Early morning late afternoon traffic congestion was reduced due to the shift of traffic from ordinary roads to expressways.
2) Traffic congestion decreased due to time shifting from peak to off-peak hours.
3) Travel time reliability was improved.
4) The roadside environment improved (e.g., noise level decreased).
5) Usage such as tourist travel increased.
6) Large-sized vehicles changed their routes.

The influences of vehicle type and discount hours on toll price elasticity of demand are listed in Figure 1 (in order, from the area with the highest elasticity to the area with the lowest elasticity). Figure 1 indicates that certain areas, such as expressway areas with small traffic volume or areas greatly affected by large-sized vehicles traveling during night, can be roughly described as having high toll price elasticity.

6.2 Discount Rate and Discount Hours

The impact of discount rates of toll was measured in detail in three locations: Iwate (Tohoku

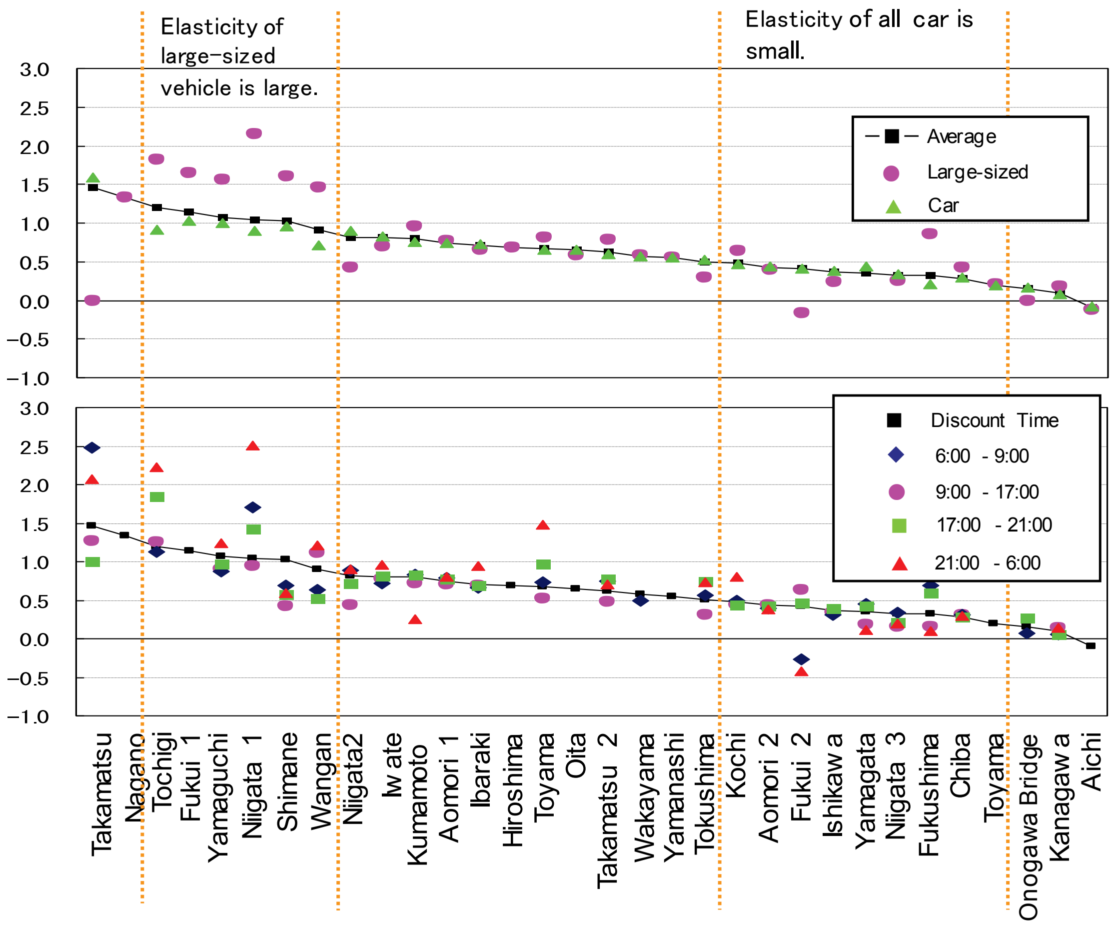

Figure 1. Elasticity of each demonstration project comparing type of car and discount time

Expressway), Hitachi (Joban Expressway), and Joetsu (Hokuriku Expressway). Table 3 shows the spot traffic volume and changes in maximum queue length for target ordinary roads, and changes in traffic volume for expressways. It also shows toll price elasticity of demand for the entire day, and for the following four time periods: early morning, daytime, late afternoon, and late night. At each demonstration project location, an increase in the discount rate resulted in an increase in expressway traffic volume. At the Iwate project, a 20% increase in the discount rate resulted in a 40% increase in expressway traffic volume. A sharp decrease in spot traffic volume and maximum congestion length on ordinary roads was also observed, but further increases in the discount rate had no clear effect. In terms of toll price elasticity of demand, the size of the discount rate had an impact on all-day toll price elasticity of demand in Joetsu, but at the other two locations, a discount rate of 30% had a greater impact than a discount rate of 50%. In addition, elasticity tended to increase late at night.

From these results, it seems certain that a discount of between 30% and 50% can produce a toll price elasticity of demand that is greater than roughly 0.8, and thus it can be assumed that the discounts contributed to the large reductions in peak-time traffic congestion (early morning and late afternoon). In the case of Joetsu, when the discount rate was 50%, the toll price elasticity of demand exceeded 1.0 throughout the day, with especially high elasticity recorded in early morning, late afternoon, and late at night. It can be said that a late-night discount causes the traffic volume of large-sized vehicles to increase, and produces a sharp increase in the toll price elasticity of demand.

6.3 Topographical and Regional Factors (Metropolitan or Regional, and Accessibility to Interchange)

In the area where toll price elasticity of demand was high for large-sized vehicles, toll price elasticity of demand for IC pairs comprising both ends of the demonstration project section for large-sized vehicles was higher compared with the toll price elasticity of demand for all IC pairs in the experiment section for all vehicle types (Table 4).

The access and egress distance to the IC pairs comprising both ends of the experiment section for large-sized vehicles was roughly within 2 km, and the ease of access to these ICs

Table 3. Change of traffic volume, congestion length and price elasticity

		Morioka		Hitachi		Joetsu	
Rate of Toll Discount (%)		30	50	30	50	25	50
Change of Traffic Volume (Ordinary Road) (%)		-3	-2	-2	-3	-3	-4
Change of Congestion Length (Ordinary Road)(%)		-65	-87	-100	-98	-30	-9
Change of Traffic Volume (Toll Road) (%)		150	190	140	160	120	180
Price Elasticity For demand	Average Full day	0.90	0.80	0.79	0.71	0.59	1.04
	AM6 – AM9	0.81	0.72	0.64	0.66	0.59	1.70
	AM9 – PM5	0.85	0.77	0.82	0.68	0.09	0.95
	PM5 – PM8	0.99	0.82	0.78	0.70	0.49	1.42
	PM8 - AM6	0.81	0.96	1.12	0.95	1.05	2.50

Table 4. Elasticity and access distance to interchanges from ordinary roads

Section of Demonstration Project	Price Elasticity for Demand			Access Distance to IC of both ends of Section (km)
	Rate of Discount (%)	Heavy vehicle IC Pair of both ends of Section	All Vehicle, All IC Pairs In Section	
Nagano	50%	1.40	1.40	0
Tochigi	50%	1.94	1.20	0
Fukui	50%	2.43	1.65	3.0
Yamaguchi	50%	2.20	1.07	2.8
Niigata	50%	2.44	1.04	1.5
Shimane	50%	1.61	1.03	0
Aomori	50%	0.93	0.74	0
Kumamoto	50%	1.65	0.82	1.1
Takamatsu	50%	1.00	0.62	0.7
Kochi	50%	0.83	0.48	0
Fukushima	50%	1.63	0.32	1.2
Hiroshima	80%	1.12	0.70	1.9

seems likely to have been a factor contributing to the route changes made by large-sized vehicles. To summarize, in the case of large-sized vehicles that need to pay a relatively higher toll per unit distance, ease of access and egress to ICs included in the relevant toll discount demonstration project section caused the traffic between IC pairs with the longest distance between both ends of the section to increase, and consequently resulted in a high toll price elasticity of demand.

6.4 Insights from the Results of the Demonstration Projects

Results from the analysis of several demonstration projects have already been explained in Sections 6.1 to 6.3. The following is a summary of the insights gained from these results.

1) Impact of time period, discount rate, etc.

   Impact of time period: Although it depends on each area's congestion hours, discounts offered during early morning and late afternoon (peak time) are effective in reducing traffic congestion.

   When different time periods are compared, late-night and night discounts tend to result in higher toll price elasticity of demand.

   Toll discount rate: A discount of either roughly 30% or 50% is effective

2) Impact of traffic on parallel ordinary roads, and of topographical characteristics

   Accessibility (distance) to an expressway affects the outcome.

   Traffic on highly congested sections of ordinary roads switches easily to expressways, and elasticity tends to become high.

   Topographical characteristics affect traffic characteristics that are sensitive to toll discounts, with the nature of this influence dependent on the specific topographical features involved.

7. DETERMINANTS OF TOLL PRICE ELASTICITY AT INTERCHANGE-LEVEL

7.1 Overview

To make further comprehensive analysis of toll price elasticity and identify the determinants of it, the regression analysis is carried out at IC-level. As already mentioned in previous sections, we have directly-measured toll price elasticities at IC-level for the highway sections targeted by the demonstration projects. Therefore, it is possible to use elasticities as a dependent variable and other influential factors as independent variables in regression analysis. Our analysis is similar with so called "meta-analysis" which is defined as the statistical analysis of analyses but in this study we carry out the statistical analysis of traffic demand at IC-level across demonstration projects.

7.2 Fundamental Analysis of Toll Price Elasticity at Interchange-Level

The demand and toll price before and after the demonstration projects are available at IC-level. We extract IC-level data from the project-level data described in previous sections. After removing negative values of elasticities, we get 368 observations of toll price elasticities at IC-level. The distribution of elasticities is shown in Figure 2 and the mean of elasticity at IC-level is 0.644 and the standard deviation is 0.388.

Since there would be unobserved common characteristics for the determinants of elasticities if they are subtracted from the same project, we also check the distribution of elasticities across different project. Figure 3 illustrates the box-plots of elasticities across projects, which indicates that the dispersion patterns of elasticities are different across different projects.

As for the relationship between toll price elasticity and potential determinants of it, Figure 4 shows the plots of the elasticity and the accessibility to the toll road, which is measured by the total distance from the competitive ordinal road to the start and end points of the corresponding IC. The result indicates that the toll price elasticity tends to diminish as the accessibility to the toll road becomes worse.

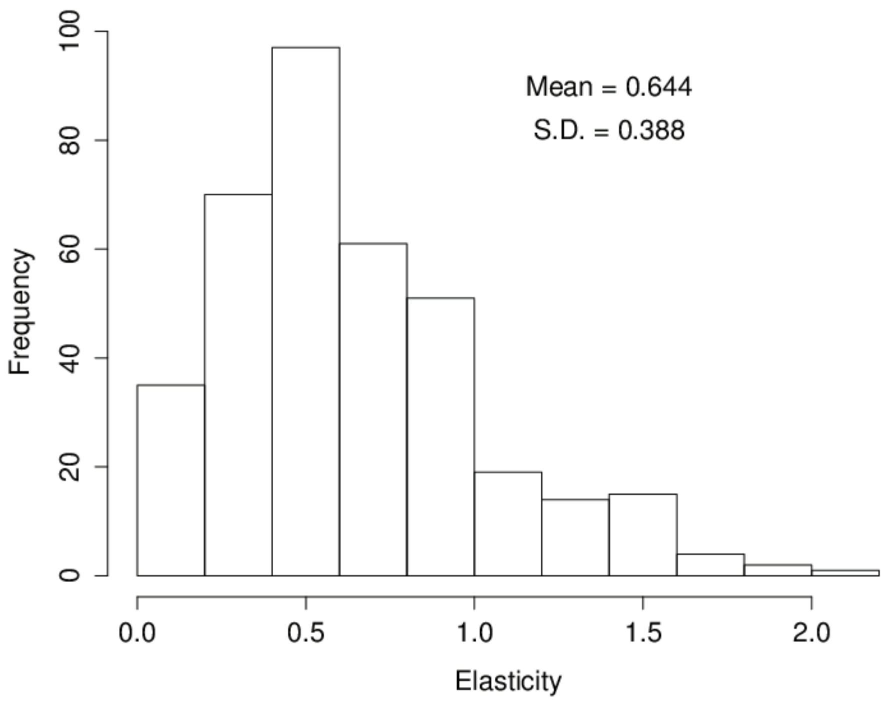

Figure 2. Histogram of toll price elasticity at Interchange-level

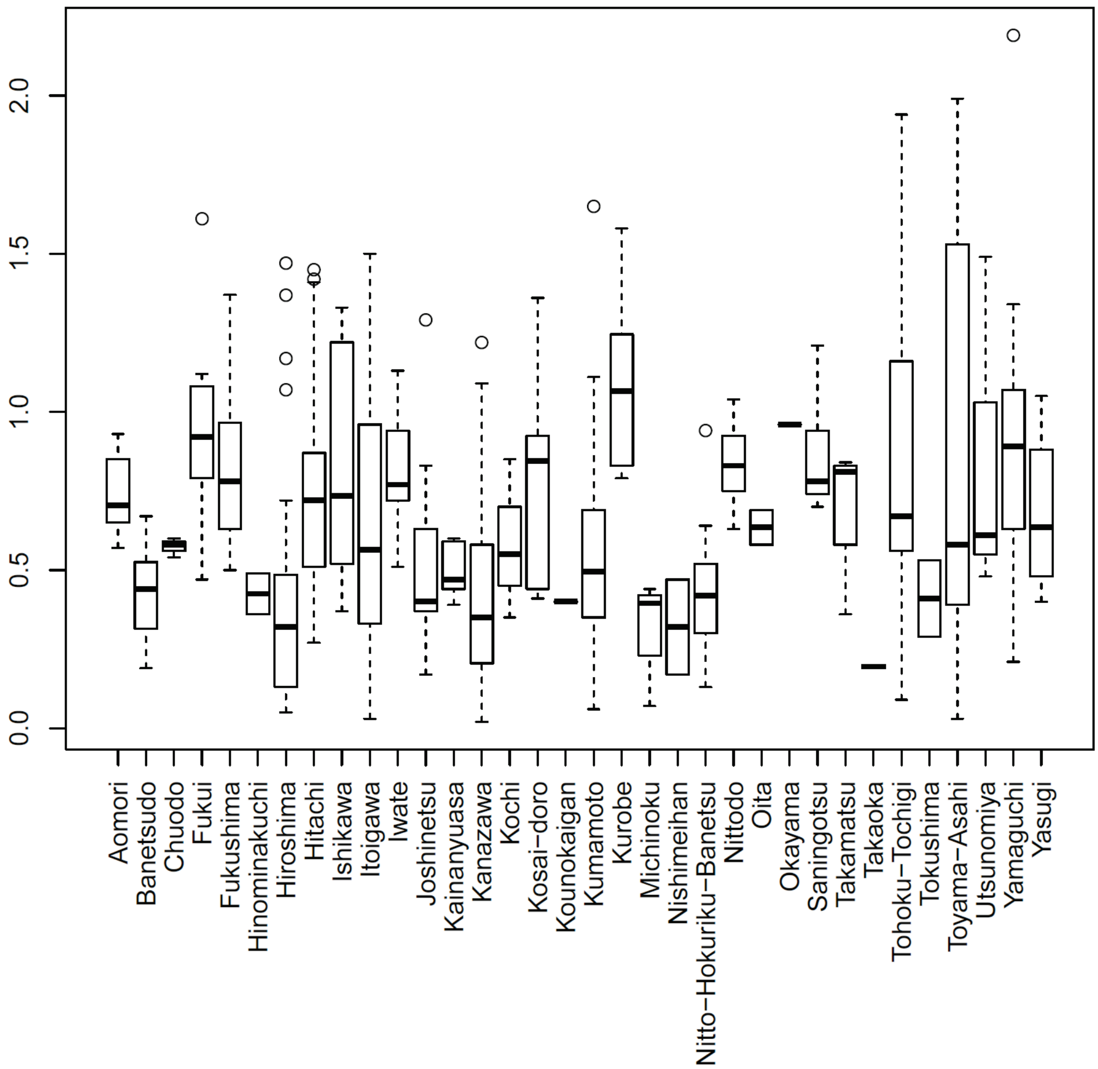

Figure 3. Box-plot of elasticities at interchange-level across projects

7.3 Regression Analysis

To make comprehensive understanding of the determinants of toll price elasticity, we perform regression analyses by taking the directly-measured elasticities at IC-level as a dependent variable. Since the elasticity takes only positive value by its nature, the following logarithmic transformation of the multiplicative model is specified:

$$\ln e = \alpha_0 + \sum_{i=1}^{n} \alpha_i \ln X_i + \sum_{j=1}^{p} \sum_{k=1}^{q-1} \beta_{jk} Z_{jk} \tag{4}$$

where e is toll price elasticity, α_0 is the constant term, there are n independent variables (X_i) as continuous scale and p categorical variables with q categories (Z_{jk}), and α_is and β_{jk}s are unknown parameters to be estimated. For categorical variables, the corresponding q-1 dummy variables are defined. We further incorporate some interaction effects of independent variables if they are statistically significant. The similar specification is, for example, applied to the meta-analysis of value of travel time by Wardman (1998).

We have carried out standard ordinary least-squares method to regress Eq (4) to estimate unknown parameters. The result is summarized in Table 5. The goodness of fit is neither fully satisfying nor disappointing. But compared with some meta-regression results in

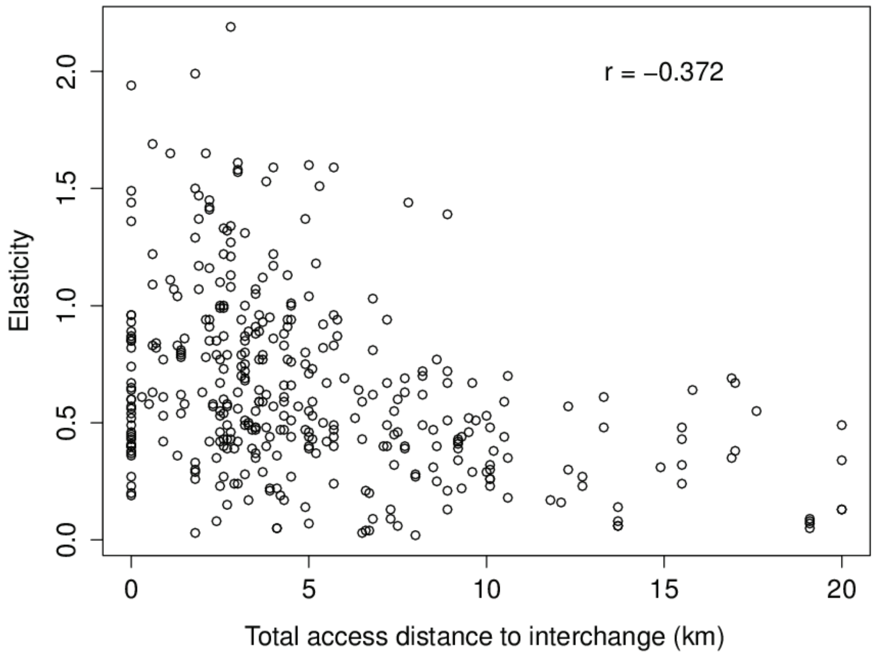

Figure 4. Relation between elasticity and toll-road accessibility

transport studies (e.g. Wardman, 1998), the adjusted R-squared takes similar value. Therefore, we use this estimation results for the following discussion on each independent variable.

The length of the toll road section has positive impact on elasticity and is highly significant, which implies that the longer the targeted section length of the toll road project is the elasticity tends to be larger. Hence, the demonstration projects with longer toll road sections are more advantageous than the ones with shorter sections in terms of elasticity.

The coefficient for the share of large-sized vehicles (e.g. trucks) of the total traffic demand is also significantly positive, which means that truck drivers/companies are more sensitive to the change in toll prices than standard-sized vehicle drivers.

The distance to access the targeted toll road has negative effects on elasticity, as already indicated in Table 4 and Figure 4. We therefore anticipate that the accessibility or the easiness to use the toll road is one of the important conditions for the success of the project by shifting larger demand.

There are some influential factors related to the characteristics of the competitive ordinary road such as number of lanes, congestion index (volume-capacity ratio) and traffic share of high-standard geometry design in the targeted toll road. The parameters of the first two are significantly positive. Therefore, if the ordinary road has been already congested or had larger capacities then the traffic demand would be shifted more by toll-pricing policies. The third factor, however, has a significantly negative effect. We interpret this that the increase of traffic would become small relative to the change in the toll price because the traffic of the toll road is already relatively large in the areas where the traffic share of high-standard geometry designs in the toll road.

The market diffusion effects of ETC strongly and negatively affects toll price elasticities. This results is consistent with the past studies (Finkelstein, 2009; Ishii and Fukuda, 2011) implying that the price sensitivity reduces due to "tax salience effects (Finkelstein, 2009)" with the cashless nature of ETC-based payment. The demonstration projects of toll prices are on the premise of ETC-based payment to shift more traffic demand from ordinal roads to the targeted toll road but this empirical finding is contradictory to that premise.

There is one significant dummy variable included in the estimation result, that is, the

Table 5. Determinants of toll price elasticity (regression result)

Variables	Estimates (Std. error)
Constant	-1.37^{***}
	(0.33)
ln(Length of the toll road section [km])	0.20^{***}
	(0.06)
ln(Share of large-sized vehicle)	0.57^{***}
	(0.12)
ln(Distance to access the targeted toll road [km] + 1)	-0.32^{***}
	(0.05)
ln(Num. of lanes for the competitive ordinary road)	0.32^{***}
	(0.10)
ln(Congestion index for the competitive ordinary road)	0.37^{***}
	(0.13)
ln(Traffic share of the high-standard design for the targeted toll road)	-0.34^{***}
	(0.09)
ln(Share of vehicles with ETC equipped)	-0.21^{***}
	(0.07)
Dummy if the project for large-sized vehicle	-0.99^{***}
	(0.36)
(Dummy if the project for large-sized vehicle) × ln(Length of the toll-road section [km])	0.13
	(0.12)
R^2	0.36
Adj. R^2	0.34
Number of observations	368

$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

dummy indicating that the project only targets large-sized vehicle (e.g. trucks). The sign of the parameter is significantly negative and it indicates that projects which aims at shifting only large-sized vehicles may not be effective.

Finally, we have tested the interaction term between the above-mentioned dummy for large-sized trucks and length of the toll-road section since it is expected that the length of the section would affect particularly the elasticity for large-sized vehicle. The estimated parameter is found to be positive as expected but its significance is small.

8. CONCLUSIONS

The paper has reported the most extensive reviews of toll price elasticities of vehicle traffic demand although focusing only on Japanese toll demonstration projects in the middle of 2000s. We have outlined multiple examples of factors that would affect the price elasticity for demand at project-level as well as IC-level. The main findings throughout the paper are as follows.

First, from the comparative analysis of some demonstration projects, the toll price elasticity tends to be larger particularly during the midnight and/or peak hours such as early morning and late afternoon. In the midnight hour, there is a large elasticity value for large-sized vehicle. We have also found that from the price elasticity value the discount rate between 30-50% would be appropriate in terms of the profitability of the projects. It has been confirmed that if the distance from ordinary roads to IC at both ends is close it would increase the elasticity and that the elasticity will be particularly advantageous in large-sized vehicles.

Second, through the detailed regression analysis to explore the determinants of toll price elasticity at IC-level we have found that there are some significant positive factors such as length of the toll-road section, share of large-sized vehicles, number of lanes, congestion index and negative factors such as total access distance to the interchanges, length share of high standard geometry design, market diffusion effects of ETC. The signs of these parameters are consistent with our intuition.

In this paper we have indicated some possible factors related to the short-term price elasticity during the period of the demonstration projects. In order to reflect the results obtained from this study to the actual pricing policy, it is necessary to further study the impact on the toll price elasticity associated with the increased use of ETC and to consider the difference to the long-term elasticity and the short-term one.

As many countries have been researching and implementing road pricing policies using ITS technologies, we would like to catch up with other reports and research outcomes and continue the relevant study to contribute to establish an effective system according to the traffic demands and characteristics of each region in Japan.

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