Viaduct maintenance for future traffic demands and earthquakes

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Econometric analysis of viaducts maintenance considering future traffic demand and earthquakes

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Abstract

Tokyo Metropolitan Expressway has operated for more than half a century. Recently, serious damages in the network have been reported in many of the old routes. In contrast, the Metropolitan Expressway has little to none of experience in managing such a situation so far. Thus, developing an appropriate management strategy focusing around maintenance is critical to the Expressway. The emphasis of this study is placed on the maintenance improvement of steel viaducts and the project aims to evaluate its marginal maintenance cost and identify the influences on the cost from uncertainties such as earthquakes and future traffic demand from an econometric perspective. The study reveals that the traffic volume of passenger cars can be identified as a significant factor although the effect of earthquake events on the cost is not clearly pronounced. Based on the analyses, it is found that the current maintenance approach is capable of dealing with fluctuation of traffic volume, which is the most influential factor. Furthermore, an increase in the amount of maintenance works could possibly lower the maintenance costs due to the existence of economy of scale. The results also indicate that the efficiency of current maintenance method could be improved.

Keywords chosen from ICE Publishing list

Roads & highways; Viaducts; Economics & finance; Maintenance & inspection

List of notation

AADT – Annual Average Daily Traffic volume

RTS – Returns To Scale

SUR model – Seemingly Unrelated to the Regression model

FGLS estimation – Feasible Generalized Least Squares estimation

Introduction

Tokyo Metropolitan Expressway Company Limited (MECL) has been established in 1959 for the purpose of reducing traffic congestion in and around Tokyo. Recently, deterioration and various kinds of damage have become prominent in its structures especially in the old expressway network. Furthermore, most of the Metropolitan Expressway consists of bridges, tunnels and semi-underground structures (Metropolitan Expressway Company Limited, 2015). Thus, it is highly important to understand maintenance costs in the structures in terms of traffic volume.

Link (2005 and 2014) analysed highway maintenance costs from an econometric viewpoint. However, he focused only on highways which consist of embankments. Hence, this study focused on maintenance costs in a steel structure which is one of the main structures in the Metropolitan Expressway shown in Figure 1 and derived the maintenance marginal cost in consideration of the influence of traffic volume. In fact, MECL needs to have its own standard to judge the best maintenance method depending on the structural damage such as general repair or structural renewal need to be established. Metropolitan Expressway Route 3 Shibuya Line ("Route 3"), which is one of the oldest expressways constructed in 1967, was focused. Especially in such old expressways, the suitable maintenance standard is assumed to be significantly important. Moreover, there have been many earthquakes and they have had large negative effects on many structures in Japan (Heath, 1995). Although it is difficult to predict earthquakes precisely, their influences on the maintenance cost should be considered. Therefore, an analysis of the effects of earthquakes as well as the effects by traffic volume was implemented. This study will play a role to judge more suitable maintenance method in consideration of future traffic volume and earthquakes.

The aim of this study is to identify the influence on the maintenance cost for a steel viaduct in Route 3 from uncertainties such as earthquakes and future traffic volume and the cost efficiency of the current maintenance method.

2. Literature review

Many economic approaches with various functions have been taken to express behaviours of producers in the past (Ferrier and Lovell, 1990 and Podolny 1993). These approaches can generally be divided into two parts. The first aims to estimate the largest profits by the use of a production function (Fare, Grosskopf and Pasurka, 2007). The other is to identify an optimal marginal cost by using a cost function. The marginal cost estimation has been conducted in various business sectors such as power generation, water utility, bus management, banking and agricultural industries (Atkinson and Halvorsen, 1984, Bottasso and Conti, 2009, Mizutani and Urakami, 1999, Viton, 1981 and Coelli, 1995). Cost functions used in past studies can be divided into two groups. The first group is a function, which has no theoretical economic background (Ford and Warford, 1969, Mann and Mikesell, 1976 and Morgan, 1977). The other is a function based on the economic corporate behaviour principle, where any enterprise seeks to minimise cost of input factors under production cost as a key criterion (Feigenbaum and Teeples, 1983, Pulley and Braunstein, 1992 and Kim, 1987). In the former, cost is regarded as explained variable and the factors considered to influence on the cost is regarded as an explanatory variable. In the latter, a cost function with an economic theoretical background expresses a mathematical formula between the cost, production output and input factor, which is demonstrated in Equation (3).

Moving on to cost function models, four types of cost function models such as linear, log linear, Cobb-Douglas and translog models were used in previous research. Linear and log linear cost function models have no theoretical economic background. On the other hand, other two types of cost function models such as Cobb-Douglas and translog models are based on theoretical economic background. Particularly, the translog cost function model introduced by Christensen, Jorgenson and Lau (1973) is more flexible than Cobb-Douglas model in terms of having the ability to deal with changeable elasticity of substitution. Thus, it can be assumed that the translog cost function model express the minimum cost of production more precisely than other models. Clark and Speaker (1994) calculated scale of economy in the banking business by use of a translog cost function. As for scale of economy, Deller, Chicoine and Walzer (1988) researched whether introduction of larger units could achieve cost saving in consideration of rural road management.

Recently, as for highway management, Link (2006) analysed renewal marginal cost in German highways and the relationship between traffic volume and the renewal cost by using the translog cost function. Furthermore, Link (2014) analysed the relationship between traffic volume and maintenance cost, and calculated the cost elasticity and the marginal maintenance cost for pricing determination. As a result of the research, a decreasing elasticity curve and decreasing marginal cost curve could be derived. Moreover, the research also provided evidence for price-inelastic factor and existence of returns to scale in the course of road maintenance. As described above, the translog approaches have been adopted to evaluate various kinds of public infrastructure industry. Meanwhile, MECL which runs the Metropolitan Expressway has consistently managed the expressway and has attached the heaviest weight to achieving the highest user convenience at a minimal cost since its establishment (Metropolitan Expressway Company Limited, 2017a). In other words, the company has not always run its expressway to maximise its profit margin as its focus is the public good. Hence, using a translog approach which is appropriate for deriving cost minimising behaviour is assumed to fit the corporate mission. Furthermore, it should be crucial for the company which owns various kinds of roads to understand their optimal maintenance cost and the factor with uncertainty which influences positive and negative impact on them. Thus, this study analysed optimal maintenance cost and the influential factors in a steel road structure nobody has ever tackled.

3. Maintenance methods for the Metropolitan Expressway

Since the total length of Metropolitan Expressway is more than 300km and its structure types have gradually become diverse since it opened, MECL created an inspectional manual for maintaining the expressway. In addition to that, MECL has undertaken effective and timely renewal of the manual. The manual shows the flow of inspection, the type of inspection depending on the purpose and the situation, the method, required skills and qualifications for a maintenance engineer and the standard for inspectional results. The criteria to judge the necessity of maintenance is quite important among it. When structures are inspected, the spots are classified according to 4 grades of seriousness listed in Table 1. Fundamentally, serious damage classified as rank A or B are regarded as needing to be repaired in the maintenance strategy. Therefore, maintenance costs analysed in this study are caused by the maintenance works for damage classified as rank A and B. Furthermore, the manual evaluates grades of damages in consideration of the effects on the performance required for a structure. As Table 2 shows, the performance can be categorised into “safety”, “usability” and “sociality”. Although safety and usability are obviously important, MECL regards sociality to be as important as other two performances. Note that “Sociality” means harmony of the expressway and the environment along it in terms of its appearance, noise, vibration and so on. The Metropolitan Expressway exists almost solely in the most densely populated areas in Japan. Therefore, the way of grading damage is assumed to be focused more on sociality than other Japanese roads.

4. Methodology

4.1 Translog cost function method

As mentioned before, many scholars have used economic approaches such as cost functions to identify relationships between cost, output and factor of production. In addition, Coelli (1995) stated a cost function can represent a minimum cost from a given series of inputs, whereas a production function can represent maximum output. Since MECL considers minimum-cost management as a corporate mission, this study also aims to identify a minimum operational cost. Specifically, a translog cost function was used to analyse the relationship between maintenance cost, traffic volume as an output, and maintenance marginal cost for a criterion to introduce a feasible maintenance plan. The analysis period was 10 years between 01/04/2007 and 31/03/2016. Characteristically, annual average daily traffic volume (“AADT”) of passenger and large-sized cars were used as a main explanatory variable. Earthquake frequency was also used as an explanatory variable. Furthermore, labour cost, material and machinery cost ("material cost"), and capital cost are necessary to implement expressway maintenance and are considered as factors of production. The damage which needs maintenance works is assumed to be reflected in levels of maintenance costs.

The meaning and derivation of a translog cost function are explained as follows. First, when x_i is factors of production and output Y is an input of factors of production, a production function can be shown below.

$$Y = f(x_1, x_2, x_3, \cdots)$$
$$x_i; factors\ of\ production \tag{1}$$

A cost function can be illustrated as a formula (2) because a production function and a cost function have antipodal relationship each other.

$$Cost = g(Y_1, Y_2, \cdots, P_1, P_2, P_3, \cdots)$$
$$Y_i: Economic\ goods\ as\ an\ output,\ P_j: price\ of\ factors\ (of\ production) \tag{2}$$

When a formula (2) is logarithmic transformed and applied to Taylor's expansion, formula (3) can be obtained.

$$lnCost = \alpha_0 + \sum_i \beta_i\, lnP_i + \frac{1}{2}\sum_i \sum_j \beta_{ij}\, lnP_i lnP_j + \sum_l \gamma_l\, lnY_l + \frac{1}{2}\sum_l \sum_m \delta_{lm}\, lnY_l lnY_m + \sum_i \sum_l \rho_{il}\, lnP_i lnY_l \tag{3}$$

In this study, expressway viaducts focused on were made of steel and constructed in 1967. AADT of passenger and large-sized cars were denoted by Y_p and Y_f as produced economic output. Moreover, if labour cost P_L, material cost P_M and capital cost P_C are defined as factors of production, a cost function can be shown below. Capital cost P_C is regarded as depreciation cost which annually needs to be paid depending on the size of the expressway asset value.

$$Cost = f(Y_p, Y_f, P_L, P_M, P_C) \tag{4}$$

In addition, higher earthquake frequencies tend to increase maintenance cost and was added as a dummy variable N to a constant term which illustrates environmental condition in the expressway structure. The essential conditions for homogeneity in price of factors and for symmetry can be illustrated below (Link, 2006).

$$\sum_i \beta_i = 1, \sum_j \beta_{ij} = 0, \sum_i \rho_{il} = 0, \beta_{ij} = \beta_{ji} \tag{5}$$

Based on this explanation above, the translog cost function used in this study can be exhibited below.

$$\begin{aligned} lnCost = c + \alpha \cdot lnN + \beta_L lnP_L + \beta_M lnP_M + \beta_C lnP_C + \gamma_p lnY_p + \gamma_f lnY_f \\ + \frac{1}{2}\left(\beta_{LL} ln^2 P_L + \beta_{MM} ln^2 P_M + \beta_{CC} ln^2 P_C + \delta_{pp} ln^2 Y_p + \delta_{ff} ln^2 Y_f\right) + \beta_{LM} lnP_L lnP_M \\ + \beta_{LC} lnP_L lnP_C + \beta_{MC} lnP_M lnP_C + \delta_{pf} lnY_p lnY_f + \rho_{Lp} lnP_L lnY_p + \rho_{Lf} lnP_L lnY_f \\ + \rho_{Mp} lnP_M lnY_p + \rho_{Mf} lnP_M lnY_f + \rho_{Cp} lnP_C lnY_p + \rho_{Cf} lnP_C lnY_f \end{aligned} \tag{6}$$

Description of variables

Cost	*: Maintenance cost (£/m*year)*	Y_p	*: Traffic volume of passenger car (vehicles/day)*
L	*: Labour cost (£/m*year)*	Y_f	*: Traffic volume of large-sized car (vehicles/day)*
M	*: Material cost (£/m*year)*	*N*	*: Earthquake frequency (numbers/year)*
C	*: Capital cost (£/m*year)*		

The cost-share functions in terms of labour, material and capital cost can be shown in equations (7), (8) and (9) by use of Shephard's lemma (Shepherd, 1970).

$$S_L = \frac{\partial lnCost}{\partial lnP_L} = \beta_L + \beta_{LL} lnP_L + \beta_{LM} lnP_M + \beta_{LC} lnP_C + \rho_{Lp} lnY_p + \rho_{Lf} lnY_f \quad (7)$$

$$S_M = \frac{\partial lnCost}{\partial lnP_M} = \beta_M + \beta_{MM} lnP_M + \beta_{LM} lnP_L + \beta_{MC} lnP_C + \rho_{Mp} lnY_p + \rho_{Mf} lnY_f \quad (8)$$

$$S_C = \frac{\partial lnCost}{\partial lnP_C} = \beta_C + \beta_{CC} lnP_C + \beta_{LC} lnP_L + \beta_{MC} lnP_M + \rho_{Cp} lnY_p + \rho_{Cf} lnY_f \quad (9)$$

The cost-share function can be rearranged below in reference to equations (7), (8) and (9) (Subal, 1997).

$$S_i = \beta_i + \sum_j \beta_{ij}\, lnP_j + \sum_l \rho_{jl}\, lnY_l \quad (10)$$

The sum of error terms is 0 because the sum of all cost shares is 1. Therefore, parameters in the function (7), (8) and (9) cannot be estimated because the error variance and the covariance matrix are singular. Thus, when cost-share functions are estimated at the same time, one arbitrary function needs to be removed from the three cost-share functions S_L, S_M and S_C. In other words, the three functions including the translog function (6) and two cost-share functions were used to estimate parameters, thereby allowing the removal of the arbitrary one. Moreover, it is presumed there is correlation between error terms in each function and each sample has no correlation (Bilodeau and Duchesne, 2000). This system is said to be seemingly unrelated to the regression model (SUR model) and it is estimated by the feasible generalized least squares (FGLS) estimation method. As stated above, maximum likelihood estimates can be found (Bilodeau and Duchesne, 2000).

4.2 Software

The author used MATLAB R2017a for the FGLS estimation (MATLAB, 2018).

4.3 Input data

This study uses the real data of maintenance costs for the Route 3. Along the route, one bridge is 27m long with 2 lanes and is assumed to be maintained routinely. This bridge was focused on, as shown in Figure 2 and 3. The road is a charged expressway in Tokyo's urban area and its AADT ranged from roughly 75,000 to 110,000 cars per day (during the analysis period). The structure consists of a steel girders and piers and it was built in 1967. Recently, maintenance works involving repairing damage have been frequently implemented. Labour and material costs spent past 10 years in maintenance works for the bridge were used as analysis data. The maintenance works include only works on the steel bridge structure, which greatly influences future maintenance strategy. Therefore, other maintenance works for pavements and other facilities were not analysed. Furthermore, the depreciation cost of the asset, which has been used for maintenance, was considered as a capital cost. Although it is necessary to understand construction cost at the time of constructed precisely for accurate calculation of the depreciation cost, there was no data relevant to the construction cost. However, this problem could be solved by use of a deflator. The deflator shows the ratio between two construction costs when similar buildings are constructed now and in the past. Herewith, the expressway construction cost in 1967 can be calculated by using the cost of the same structural expressway construction recently. The equation below based on the present value of the expressway bridge and relevant ratios calculates its depreciation cost defined by National tax agency in Japan (National Tax agency, 2017). The present value is calculated by use of the construction cost mentioned before and maintenance cost which increases asset value. Furthermore, the durable life of the expressway is determined by its physical life. The depreciation procedure needs to be continued until the price becomes 10% of its acquisition cost in case the expressway asset value increased.

$$Depreciation\ cost\ per\ year = P \times 0.9 \times 0.023$$

$$P: Present\ value$$

$$0.9: Ratio\ of\ total\ depreciation\ cost$$

$$0.023: Depreciation\ rate\ per\ year$$

(11)

For the reasons aforementioned, 3 types of costs such as labour, material and capital cost were regarded as factors of production. The price of the factors, passenger and large-sized cars' AADT, and earthquake frequency are set as explanatory variables for maintenance costs listed in Table 3. Large-sized cars are defined as coaches, large trucks, trailers and special vehicles such as construction vehicles. Although it was desirable to use vehicle load data, two types of data mentioned before were used for analysis because of having no access to axle-load data. Therefore, the results were limited to the figures for average passenger and large-sized cars without considering detailed weight classes. The intensity of earthquakes was limited to more than what people can feel, as per the Japan Meteorological Agency seismic intensity scale. The official scale does not show the scale of earthquake itself but shows the intensity of shaking caused by earthquakes at an observation point. Moreover, the scale has 10 grades specified by accelerometers. By definition, if the seismic intensity is more than 1, the earthquake can be physically felt by people. In addition, traffic volume was derived from traffic counters densely allocated along the expressway. Data gaps were assumed not to affect the results because the failures of devices and their deficits are quite small. Although Link (2005) used the number of days, which had temperature fluctuations around 0 degrees Celsius as an explanatory variable for the renewal cost in German highways, this study does not use the explanatory variables due to the relatively small amount of available data in Tokyo.

4.4 MATLAB feasible generalized least squares (FGLS) estimation

Parameter estimation was implemented by use of the translog cost function and cost share equations as explained in section 4.1. Since 10 years' data from 2007 to 2016 was analysed, a total of 30 equations were used to estimate parameters. The data and program code utilized in the estimation are listed in Figure 4 and 5.

5. Input data analysis

This section focuses on input data used in parameter estimation. This data includes the number of earthquakes, AADT of passenger and large-sized cars, and factors of production. First, number of earthquakes shown in Figure 6 is checked. The earthquakes focused are large enough to feel by human. In addition, they are only available and objective data observed in Japan Meteorological Agency (Japan Meteorological Agency, 2018). As shown in the figure, the number of earthquakes decreased from 2007 to 2009. However, it suddenly rose in 2010 and was also high in 2011. The rise was believed to be influenced by the occurrence of Great East Japan earthquake and its aftereffects. Although the earthquake occurred in March 2011, Figure 6 illustrates it in 2010 because the Japanese annual fiscal year from April to March was used. After that, the earthquake frequency decreased from 2012 to 2015, and then it slightly increased in 2016.

Second, the AADT of passenger and large-sized cars is shown in Figure 6. These two kinds of traffic have gradually decreased in volume over the last 10 years. Especially in 2010, the volume significantly decreased. A possible reason was that a new ring road was partially opened in 2010. The ring road called the Central Circular route is expressed by a red line in Figure 7 and acted as an alternative to Route 3. As a result, the traffic volume decreased. As for passenger cars, traffic volume remained at the same level from 2010 to 2016. On the other hand, traffic volume of large-sized cars continued to decrease after 2011. The Central Circular Route has possibly influenced large-sized cars more than passenger cars.

Third, factors of production focused in the research are explained. Labour and material cost showed similar movement during analysis period. This was possible because these two types of costs were mainly for maintenance works. In addition, capital costs showed increasing trend for 10 years. This movement was assumed to be highly related to expressway asset value.

Lastly, future prospects are explained. As for earthquake frequency, it is difficult to estimate it precisely. However, it is possible to estimate traffic volume to some extent. First, the Olympic Games will be held in Tokyo in 2020. Although traffic demand in Tokyo metropolitan area will be higher, Tokyo Metropolitan Government will aim to cut the traffic volume in the area during the

Olympic Games by 15 percent from general weekly levels (The Japan Times, 2018). In addition, the three ring expressways connecting the Greater Tokyo Area will be completed in the near future as shown in Figure 7 (Tokyo Metropolitan Government Bureau of Construction, 2018). These events could have effects on the traffic situation. In particular, the completion of the three ring expressways could make traffic flow much smoother and more effective (Oguchi, Chikaraishi, Iijima et al., 2016), as a result, the traffic volume in radial expressway routes such as the Route 3 will decrease after the completion of the three ring expressways.

6. Estimation Results

6.1 Parameter estimation

Table 4 shows the regression estimate results by use of the translog cost function and the cost-share functions explained in the previous section. It is assumed the results of the estimation are largely confirmed to be statistically stable without γ_p, γ_f, β_{CC} and ρ_{Cp} due to standard error. On the other hand, the influence on maintenance cost by earthquake frequency and capital cost cannot be confirmed because the coefficients are too small, which means capital cost is not a supportive coefficient in this case. Moreover, since parameter γ_f is shown to be a negative value, the traffic volume of large-sized cars possibly decreases maintenance costs. Actually, traffic volume is not measured by an axel load of each vehicle but by a length of each vehicle. Generally speaking, weight directly influences on structure deterioration. Thus, the phenomenon could possibly occur because of the measuring method of traffic volume on the expressway. Furthermore, the estimation accuracy of parameter γ_f is low. Hence, additional parameter estimation is conducted afterwards.

6.2 Price elasticity

Price elasticity can be calculated from the estimated parameters. That price elasticity can be divided into the elasticity between any pair of input factors and the own-price elasticity of each factor. These two kinds of elasticities can be calculated by applying the Allen-Uzawa substitution elasticities (Uzawa, 1962).

$$\varepsilon_{ii} = \frac{\beta_{ii} + S_i(S_i - 1)}{S_i^2}$$

$$i = L, M, C$$

$$\varepsilon_{ii}: Own - price\ elasticities\ of\ each\ factor$$

(12)

$$\varepsilon_{ij} = \frac{\beta_{ij} + S_i \cdot S_j}{S_i \cdot S_j}$$

$$i, j = L, M, C$$

$$\varepsilon_{ij}: Substitution\ elasticities\ between\ any\ pair\ of\ input\ factors$$

(13)

A transition of own-price elasticities of three factors are shown in Table 5 and Figure 8 by use of parameter estimation in the previous section. As a result of the transition, labour and material costs are substitutes because of their values being less than 0, while capital cost can be understood as a complementary factor. Even if capital cost rises, the demand will increase. Ryan and Wales (1999) stated translog cost functions needed to be concave in prices, in addition, the Hessian matrix of the cost functions should be negative semidefinite as a necessary condition for concavity. This is the same as the cost minimizing condition. In other words, capital cost does not meet the cost minimizing condition. As mentioned before, parameter estimation of capital cost is still in doubt in terms of its accuracy. Thus, parameter estimation without a factor of capital cost needs to be implemented. However, as mentioned in 6.1 section, the influence of capital cost is quite small. In other words, the influence can be discounted. Thus, the analysis with the parameter shown in Table 4 will also be implemented continuously. The translog function and cost share functions without a factor of cost function used in the estimation are as follows.

$$\begin{aligned} lnCost = c + \alpha \cdot lnN + \beta_L lnP_L + \beta_M lnP_M + \gamma_p lnY_p + \gamma_f lnY_f \\ + \frac{1}{2}\left(\beta_{LL} ln^2 P_L + \beta_{MM} ln^2 P_M + \delta_{pp} ln^2 Y_p + \delta_{ff} ln^2 Y_f\right) + \beta_{LM} lnP_L lnP_M + \delta_{pf} lnY_p lnY_f \\ + \rho_{Lp} lnP_L lnY_p + \rho_{Lf} lnP_L lnY_f + \rho_{Mp} lnP_M lnY_p + \rho_{Mf} lnP_M lnY_f \end{aligned}$$

$$S_L = \frac{\partial lnCost}{\partial lnP_L} = \beta_L + \beta_{LL} lnP_L + \beta_{LM} lnP_M + \rho_{Lp} lnY_p + \rho_{Lf} lnY_f \quad (14)$$

$$S_M = \frac{\partial lnCost}{\partial lnP_M} = \beta_M + \beta_{MM} lnP_M + \beta_{LM} lnP_L + \rho_{Mp} lnY_p + \rho_{Mf} lnY_f \quad (15)$$

(16)

The results of parameter estimation are listed in Table 6. First, estimation accuracy of parameters is assumed to be significantly improved more than previous estimation in terms of standard error. However, parameter tendency as the results show is quite similar to the previous estimation shown in Table 4. Thus, it cannot be stated unconditionally that the results of previous estimation have a problem in their accuracy. In addition, it is assumed traffic volume of passenger cars and maintenance cost have a proportional connection because of two reasons as follows. One is the value γ_p is greater than γ_f according to the results. The other is traffic volume of passenger cars is significantly higher than that of large-sized cars. However, the influences on maintenance cost by passenger and large-sized cars need be considered.

As for own-price elasticities, all figures illustrated in Table 7 and Figure 9 are less than 0, thereby showing the existence of the own-price elasticities over an entire period. Therefore, the results are consistent with cost minimizing conditions. On the other hand, in comparison with labour and material costs as factors of production, these two factors are close to 0 as Figure 8 shows. Therefore, labour and material costs do not necessarily have price elasticities.

Secondly, the results of substitution elasticities shown in Table 8 and Figure 10 are explained. Although the figures of labour and material costs are positive, they are close to 0. Thus, these two factors of production are independent rather than substitutes. On the other hand, for reference purposes only, other substitution elasticities from previous estimations shown in Figure 10 were more than 0 over an entire period and expressed considerably similar movements. Therefore, it is assumed these two kinds of elasticities can be substitutes. The movement was highly influenced by the transition of the three cost factors.

Price elasticities are focused on in this section. Labour and material cost are independent factors as for substitution elasticity. Moreover, though there is a problem about estimation accuracy in capital cost, as for own-price elasticity, both labour and material cost have also shown independent trends. Labour and material costs are assumed to not be substitutes nor complements because of their roles, though both of them are essential for maintenance works. Moreover, capital cost is assumed to have a strong relationship with the maintenance quantity which influences expressway asset value. Furthermore, according to the rising quantity of maintenance works as a result of Great East Japan earthquake in 2011, expressway asset value, capital cost and the price elasticity have temporally increased. Demand fluctuation for maintenance can influence considerably capital cost.

6.3 Returns to scale (RTS)

Next, returns to scale (RTS) is analysed. The definition is generally to be the proportional increase in outputs that would result from a proportional increase in all inputs (Panzar and Willig, 1977). The expressway focused is one of the main roads in Tokyo’s central area. Furthermore, its traffic volume is forecasted to fluctuate in the future due to the completion of the three ring expressways and the Tokyo Olympic Games. Thus, getting a grasp of RTS is important. However, there are two cases of RTS. One is a situation that only one output such as traffic volume of passenger cars or large-sized cars increases N times more than before when maintenance cost increases N times more than before. Another situation is all outputs increase N times more than before in the same situation mentioned before. Although plural outputs such as traffic volume of passenger and large-sized cars are considered, these two outputs are assumed to be correlated with each other. Hence, the latter situation is more appropriate for this study. The latter situation, known as overall scale economies, can be shown by transforming the translog function (17). If the size of the result is less than 1, RTS is regarded to come into play (Noulas, Ray and Miller, 1990). In this study, if RTS can be confirmed, less input such as maintenance cost can generate same amount of output as current one.

$$RTS = \sum_{l} \left(\frac{\partial lnCost}{\partial lnY_l} \right)$$
$$= \beta_p + \beta_f + \delta_{pp} lnY_p + \delta_{ff} lnY_f + \delta_{pf} lnY_f + \delta_{pf} lnY_p + \rho_{Lp} lnP_L + \rho_{Lf} lnP_L$$
$$+ \rho_{Mp} lnP_M + \rho_{Mf} lnP_M + \rho_{Cp} lnP_C + \rho_{Cf} lnP_C \quad (17)$$

The results are shown in Table 9 and Figure 11. The value of RTS remained close to 0 from 2007 to 2016 as is the case with the previous estimation. Therefore, existence of RTS can be found from the results because the value during the entire period has been less than 1. Hence, less maintenance cost as input can generate same traffic volume as output if the situation is same as current condition. For example, if the amount of maintenance works is increased and the works are done all at once, the maintenance cost can be reduced.

6.4 Marginal maintenance cost

Marginal cost for maintenance works is evaluated based on parameter estimation calculated in the previous section. Since traffic volume of passenger cars is considered to be the most influential factor, the relationship between traffic volume and marginal maintenance cost needs to be confirmed. If marginal maintenance cost is considerably influenced by change in traffic volume of passenger cars, current maintenance method has room to be improved for cost efficiency. However, if the change has little effect on maintenance cost, current maintenance method assumed to be cost-effective. In the calculation of marginal maintenance cost, 10 years' average data for earthquake frequency, large-sized cars AADT, labour, material and capital cost are used. The results are listed in Figure 12, which consists of the parameters by use of the renewal translog model (14) and the parameters shown in Table 4 derived from first translog model (6) as a previous estimation. The difference between these two estimations is present with or without capital cost. As a result, these two models displayed the same tendencies. First, marginal cost significantly increases between 0 and 30,000 cars per day. Then, the cost remains almost the same when traffic volume rises. Thus, even if traffic volume considerably fluctuates from its current situation of about 60,000 cars per day, it is assumed maintenance cost will not drastically change by use of the current maintenance method. In other words, current maintenance method is assumed to be economically efficient.

7. Conclusions

The Metropolitan Expressway recently has suffered serious damage especially in the old routes. Therefore, optimal maintenance methods for the expressway have been more important than before. This study focused on maintenance cost in a steel viaduct in “Metropolitan Expressway Route 3 Shibuya Line”, and analysed the marginal maintenance cost and the influences on the maintenance cost from uncertainties such as earthquakes and future traffic volume from an econometric perspective. As for analysis method, labour, material and capital costs related to the viaduct maintenance are evaluated as input factors for a translog cost function. In addition, traffic volume of passenger and large-sized cars are used as output to calculate price elasticities of input factors, RTS and a marginal maintenance cost.

First, in parameter estimation, the result indicated traffic volume of passenger cars was the most influential factor of maintenance cost. On the other hand, this study could not confirm the influence of earthquake frequency on the maintenance cost. Although the Great Hanshin-Awaji Earthquake in 1995 actually caused destructive damage to many infrastructure facilities such as the Hanshin Expressway bridges (Miki and Sasaki, 2005), some seismic countermeasures of both current reinforced concrete and steel piers were implemented in addition to the introduction of new seismic design afterwards (Yasuda and Ogasawara, 2004). Such countermeasures are assumed to minimise the negative effects of earthquakes. As a result, it is assumed the effect of earthquakes on maintenance cost were not observed.

As for own-price elasticities, labour and material costs showed independent tendencies. Moreover, the results are quite similar those outlined by Link (2014). However, capital cost showed a complementary tendency. The tendency means the capital demand will rise later on when the cost increases. That can be easily estimated from the relationship between depreciation cost which consists of capital cost and expressway asset value. In other words, it is assumed the results showed the actual movement of the costs well.

Furthermore, RTS was consequently confirmed as Link (2014) suggested. Therefore, current traffic volume can be maintained by use of less maintenance cost than current one in the following situation. If the amount of maintenance works is increased and the works are done all at once, the more cost-effective maintenance can be achieved.

As for marginal cost, even if traffic volume significantly fluctuates, it is highly possible maintenance cost will not change considerably. In other words, maintenance cost will not drastically change if the current maintenance method continues to be used.

Lastly, according to the analysis of the results, the current maintenance method should not be changed immediately in consideration of cost minimisation and optimal cost. Furthermore, fluctuation of traffic volume in the future can be dealt with if the number of AADT passenger cars considerably changes. On the other hand, despite it being said maintenance cost is mainly influenced by traffic volume of large-sized cars (Link 2006), the analysis results indicated traffic volume of passenger cars had the most impact on maintenance cost.. Future work includes data collection and analysis of detailed vehicle classifications in order to improve financial strategy and structure of Tokyo expressway access fee.

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Figure captions

Figure 1. The map of Metropolitan Expressway (permission obtained from Metropolitan Expressway Company Limited)

Figure 2. The bridge span focused on in the study (ground plan) (permission obtained from Metropolitan Expressway Company Limited)

Figure 3. The bridge span focused on in the study (cross section) (permission obtained from Metropolitan Expressway Company Limited)

Figure 4. Data list for parameter estimation (permission obtained from the author)

Figure 5. Program code for parameter estimation (permission obtained from the author)

Figure 6. AADT and number of earthquakes (permission obtained from the author)

Figure 7. The three ring expressways (permission obtained from Tokyo Metropolitan Government)

Figure 8. Own-price elasticities of each factor (permission obtained from the author)

Figure 9. Own-price elasticities of labour and material factors (permission obtained from the author)

Figure 10. Substitution elasticities between labour, material and capital cost (permission obtained from the author)

Figure 11. Returns to Scale (RTS) (permission obtained from the author)

Figure 12. Marginal maintenance cost per meter (permission obtained from the author)

Table captions

Table 1. 4 grades of damage in inspection (permission obtained from Metropolitan Expressway Company Limited)

Table 2. 3 types of damage and their effects on performance of structures (permission obtained from Metropolitan Expressway Company Limited)

Table 3. Descriptive analysis of 1 span in Metropolitan Expressway Route 3 (permission obtained from Metropolitan Expressway Company Limited)

Table 4. Results of the translog model for Metropolitan Expressway maintenance cost (permission obtained from the author)

Table 5. Results of the own-price elasticities of each factor (permission obtained from the author)

Table 6. Results of the renewal translog model for the maintenance cost (permission obtained from the author)

Table 7. Results of own-price elasticities of labour and material factors (permission obtained from the author)

Table 8. Results of substitution elasticities between labour and material cost (permission obtained from the author)

Table 9. Returns to Scale (RTS) (permission obtained from the author)