The Optimal Toll Management of Urban Expressway with Long Term Variable Traffic Demand

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Abstract: The toll system has been applied in urban expressway in Japan to redeem the construction costs and maintenance expenses. In particular, the distance based toll has been introduced with electric toll collection (ETC) installation since 2012. According to the sustainable transport, the redemption plan should be determined with distance based toll for long term. The traffic demand might be varied reflecting to the economic activities and population in future. On the other hand, the maintenance expense might increase corresponding to the period of expressway service. The objective of the study is to provide the management method to optimize the time series of the distance based toll of expressway with referring to variable future traffic demand.
The calculation of traffic assignment model has a great effort, and only key indices are used for evaluation. Therefore, a neural network which is one of intelligent information processing techniques is used. It is possible to calculate the evaluation index without calculating traffic assignment model. As a result of analysis of the long-term redemption possibility, a long-term management policy and rules are proposed for sustainable road management.
The time series demand response toll system would be proposed for long term sustainability.

Keywords: Toll Management, Urban Expressway, Traffic Assignment Model

1. INTRODUCTION

Urban expressway has been constructed to produce the smooth traffic in the urban area for over fifty years. The study is examined Hanshin expressway and urban transport network in Keihanshin area. The length of the urban expressway is counted as 259.1 km in 2013. The urban expressway consists of 18 routes connecting to the suburban area from centre of Osaka. Furthermore, the inflow traffic is counted as about 740,000 vehicles per day in average. The long term repayment plan should be required to construction cost of urban expressway. The period of redemption is determined as 45 years. The construction cost should be repaid with the revenue of toll paid by expressway users and the received interest. Therefore, the long term estimation of inflow traffic into the urban expressway is essential problem to measure the revenue of urban expressway and traffic condition in future.
In the study, a long-term management policy and rules are proposed for sustainable road management. The redemption is the repaying of construction costs of urban expressways with toll revenue in the long term. Due to population decrease, economic activity situation, the number of road user may decline in the long term. Also, the maintenance and renewal expenses are expected to increase due to aging of road facilities.
The neural network approach is discussed in the study to estimate the time series traffic

demand on the urban expressway.

2. LONG TERM TRAFFIC DEMAND OF URBAN AREA

Figure 1 shows the overview of urban road network in Keihanshin metropolitan area. The urban road network consists of urban streets and urban expressways. The uniform toll system had been applied in urban expressway for over forty years. Because of urban expressway networks extension and increase of long distance trips, the distance toll system has been applied on urban expressway since 2012.

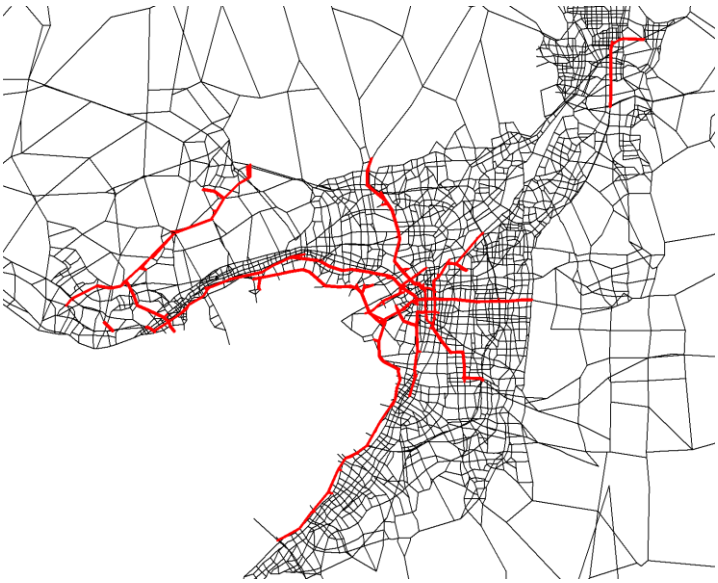

Figure 1. The outline of urban road networks

Figure 2 demonstrates the distance based toll using the step function of urban expressway in real field in 2015. The lower limit of the toll is 500 yen, the upper limit is 900 yen, and the step is 100 yen. The general forms of the distance based toll with scale parameters are illustrated as well.

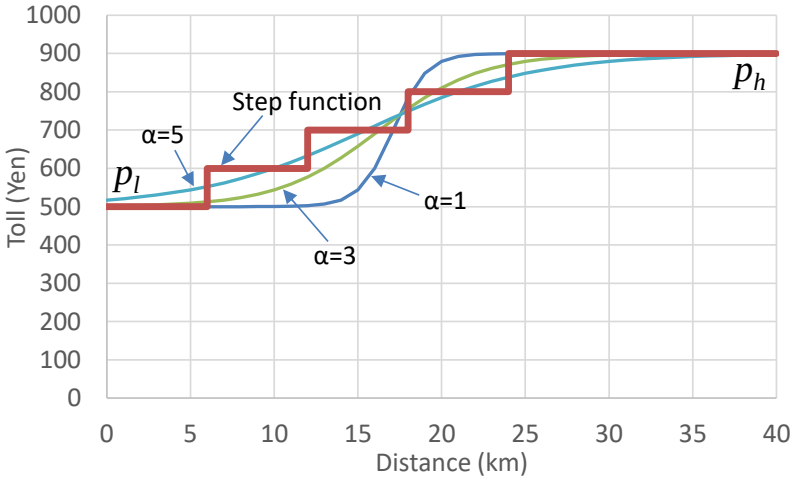

Figure 2. The distance based toll system of urban expressway

The inflow traffic of urban expressway has been increased as the length of expressway is extended. The time series of daily inflow traffic and revenue of toll can be shown in Figure 3.

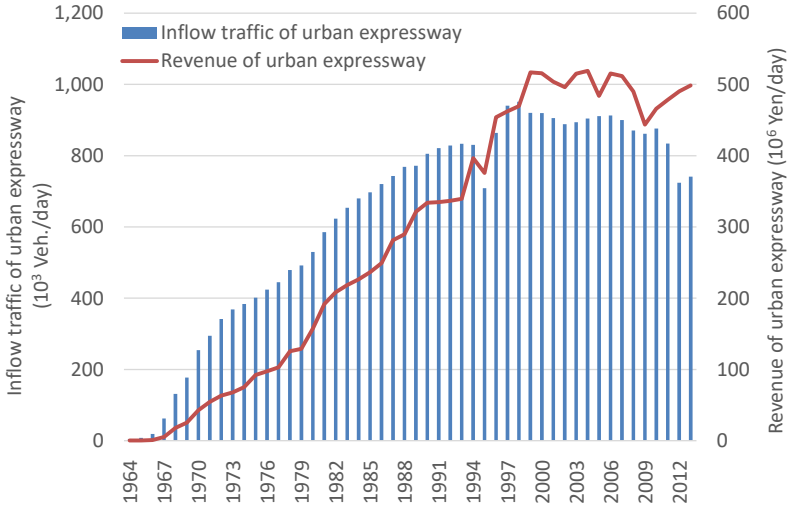

Figure 3. Time series of traffic condition of urban expressway

The daily inflow traffic had been increased from opening business in 1964 to 2002. The reduction of traffic can be found once in 1995 with damage of the Great Hanshin Earthquake. On the other hands, the decrease of traffic can be found recently according to the population decline as well as economic conditions.

The revenue of toll can be observed similarly according to the extension of urban expressway. The uniform toll system had been applied with three areas until 2011. The distance based toll system has introduce since 2012.

The estimation model of trip production volume on urban area is created. The traffic volume data can be obtained in Keihanshin metropolitan area in 1977 to 2010. It is assumed that the trip production is estimated by the population and gross domestic product as GDP of Osaka prefecture.

Linear function is applied to describe the trip production as follows:

$$TRF_t = \hat{\beta}_1 \cdot POP_t + \hat{\beta}_2 \cdot GDP_t \tag{1}$$

where,

TRF_t is the trip production of Keihanshin metropolitan area at t year (vehicle),

POP_t is the population of Osaka prefecture at t year (person),

GDP_t is the gross domestic product of Osaka prefecture at t year (10^6 Yen).

The estimation result is summarized in Table 1.

Table 1. Result of the partial regression coefficient by estimate

Explanatory variable	Coefficient	t-statistics
β_1 : Population (person)	1.529	10.21
β_2 : GDP (10^6 Yen)	0.3228	8.29
r^2	0.999	
RMSE	0.778×10^6	

Coefficient of determination is 0.999 and both coefficients are determined significantly according to t-statistics. The root mean square error (RMSE) is rather small as well to confirm

the estimation of high accuracy.
Figure 4 demonstrates the observed as well as estimated values of trip production in Osaka area respectively. The time series change of trip production can be estimated properly.

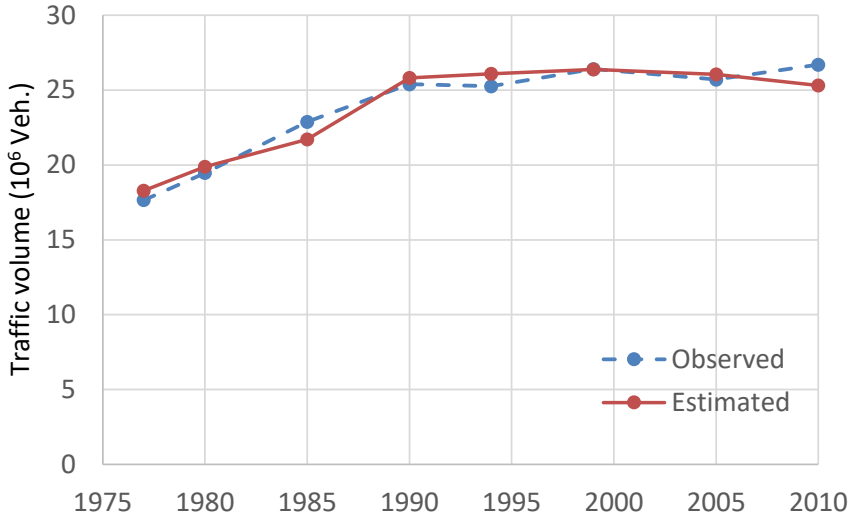

Figure 4. The estimation results of traffic volume in urban areas

In the study, the trip production is estimated at Keihanshin metropolitan area. The Keihanshin metropolitan area is larger than the urban expressway network. The volume of the trip production is about 25 million, and the number of urban expressway user is about 0.85 million. Therefore, the impact of the change in toll setting for the trip production of Keihanshin metropolitan area is small.
The independent values such as population and should be determined before future estimation. Figure 5 demonstrates the future population in Osaka prefecture estimated and reported by National Institute of Population and Security Research.

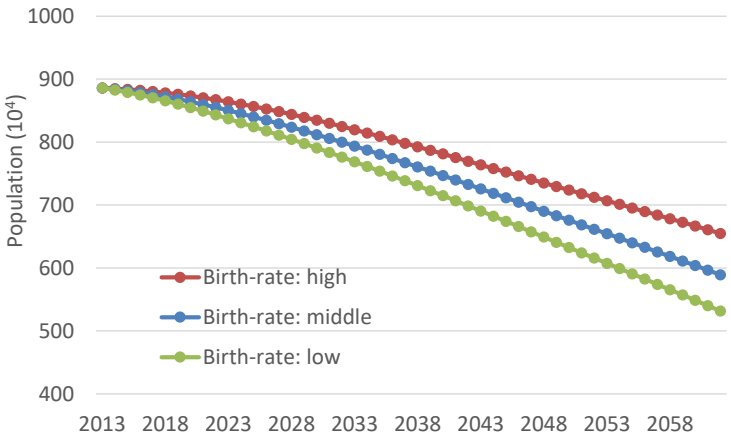

Figure 5. Estimation of future population in urban area

Figure 6 illustrates the future estimation of GDP for Osaka prefecture reported by Asia pacific institute of research. This value is basically estimated from changes in the labour force. According to this estimation result, the economic activity of the Osaka prefecture will increase for several years from 2013, and furthermore, the economic activity is supposed to diminish.
The network traffic flow on urban network involving urban expressway can be estimated by

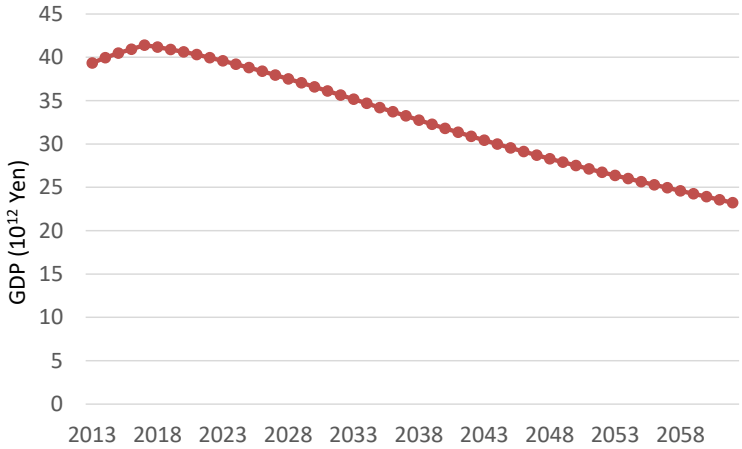

Figure 6. Estimation of future GDP of Osaka

traffic assignment technique corresponding to the estimated trip production in future. The origin destination matrix can be estimated with uniform growth factor method. According to the user equilibrium traffic flow on the network, the inflow traffic of urban expressway and toll revenue of urban expressway can be estimated for each year. Future traffic demand of urban expressway is illustrated in Figure 7.

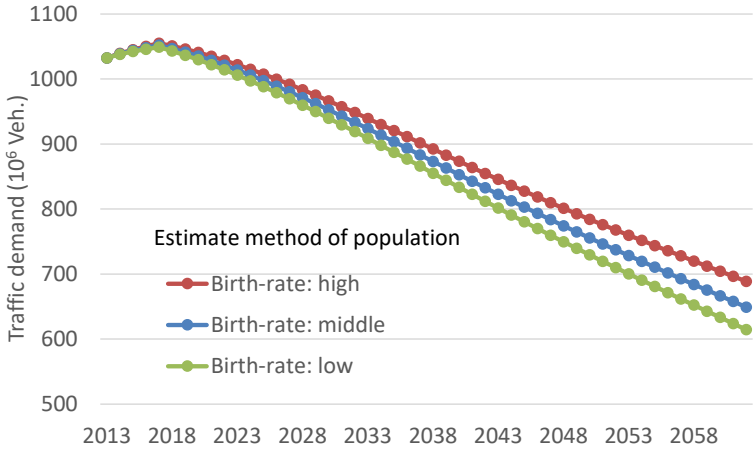

Figure 7. Estimation of future traffic demand on urban area

As shown in this figure, three type traffic volume estimates are calculated reflecting future population estimation results. In both cases, the long-term decreasing trend of the traffic demand of the whole urban road network is shown.

3. REDEMPTION PLAN WITH LONG TERM TRAFFIC DEMAND

Since the traffic demand is reduced in future, the toll revenue of urban expressway tends to be reduced as well. The redemption plan of urban expressway can be summarized. The outline of redemption plan is illustrated in Figure 8.

The duration time of redemption is counted as T. It is indicated respectively such as TCC : total cost of construction of urban expressway, TCM: total cost of maintenance, and TRT: Total revenue of toll. Finally, it is required that the value of TRT is equivalent to total cost as TCC+TCM.

In the study, numerical example can be determined with referring to Hanshin expressway. The period of redemption is defined as 50 years. Interest rate is assumed to be 4 %. The

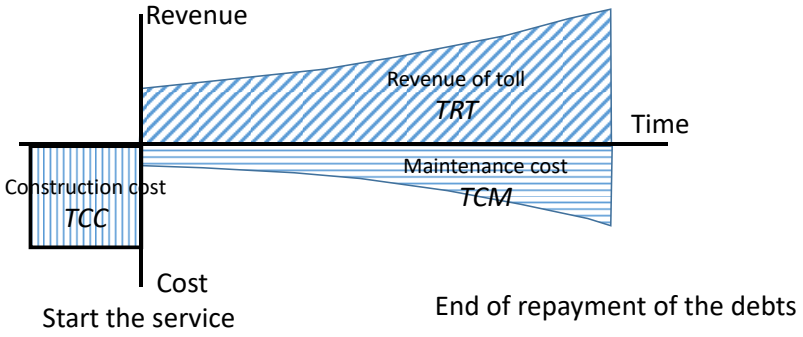

Figure 8. Redemption scheme of urban expressway

Table 2. Representation of urban networks

Total number of links	7,794
Links for streets	6,963
Links for urban expressway	481
On-ramps	174
Off-ramps	176
Number of nodes	5,264
Nodes for streets	4,798
Nodes for urban expressway	466
Centroids	400

initial construction cost (CC) is defined as 3,000 billion yen. Therefore, TCC and TCM are estimated as 21,300 billion yen and 5,000 billion yen.

The traffic assignment with representation of toll charge should be applied to evaluate the impact to traffic flow by the different price of toll. However, the great effort is required for traffic assignment to large scale network. In the study, the approximation method would be proposed using the advanced information processing approach.

Neural network model is applied to estimate the network statistics approximately. Figure 9 illustrates the outline of neural network model. The connecting weights are estimated with the training data. Back propagation approach is applied to determine the weights. Three layered neural network model is created.

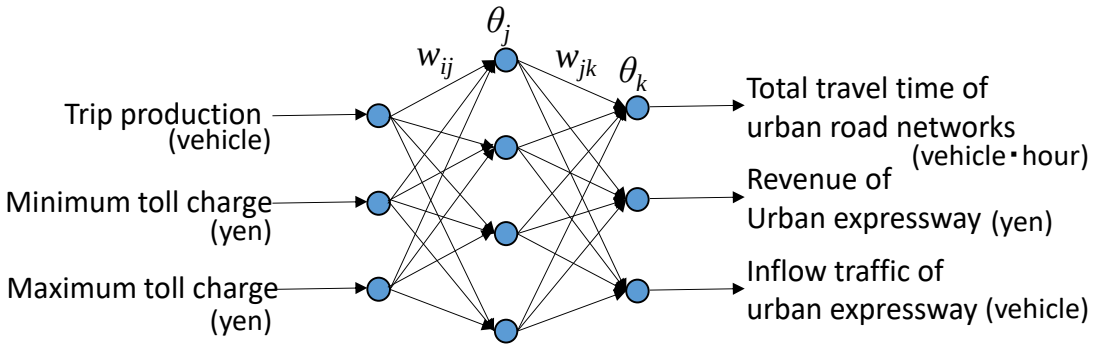

Figure 9. Representation of neural network model

As shown in Figure 9, the trip production, the lower limit of toll (point p_l in Figure 2) and upper limit of toll (point p_h in Figure 2) are used as the input of the neural network model. Because, the optimal pricing will change depending on the amount of trip production.
The output indicator uses the total travel time of whole urban road network, the toll revenue of urban expressway and the number of vehicles using urban expressway. These indicators are basic items for evaluation.
The non-linear relationship between toll type and revenue can be determined with neural network model. Different function of minimum and maximum value of toll can be determined corresponding to the traffic demand for Osaka area. Figure 10 illustrates the relation between the toll level and revenue of toll with different traffic demand. As a general trend, when the future traffic demand of the urban road network is relatively small, toll revenue increases as the upper and lower toll small. On the other hand, if the demand for traffic in the future is relatively large, the toll revenue increases when the toll level is high.

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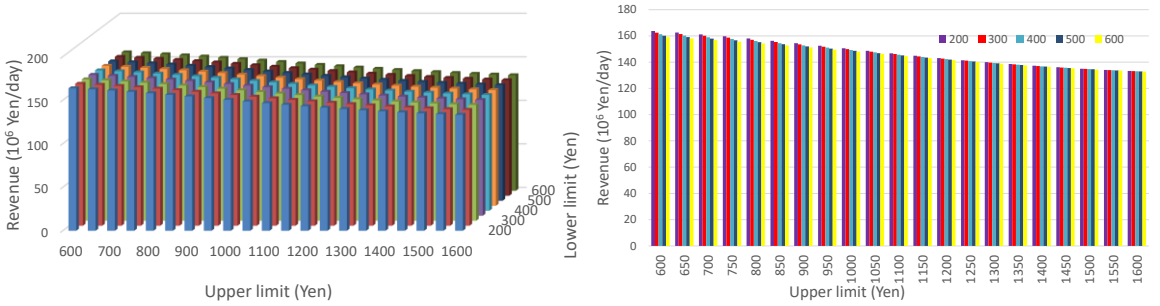
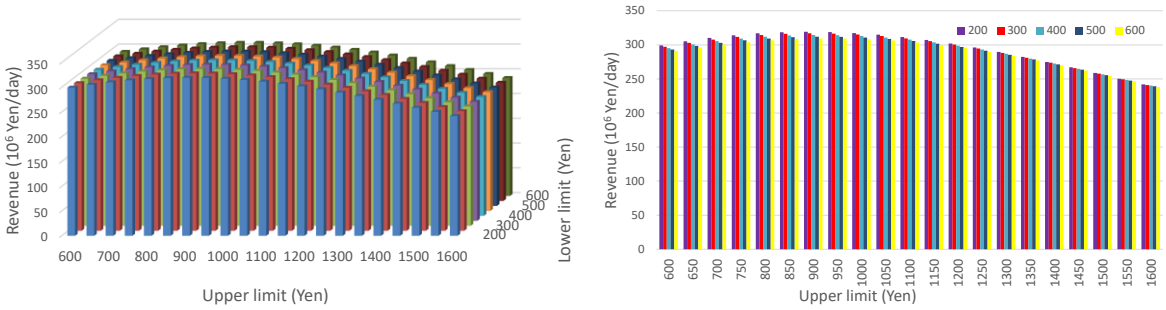


Q=8,000,000 (Veh./day)



Q=10,000,000 (Veh./day)

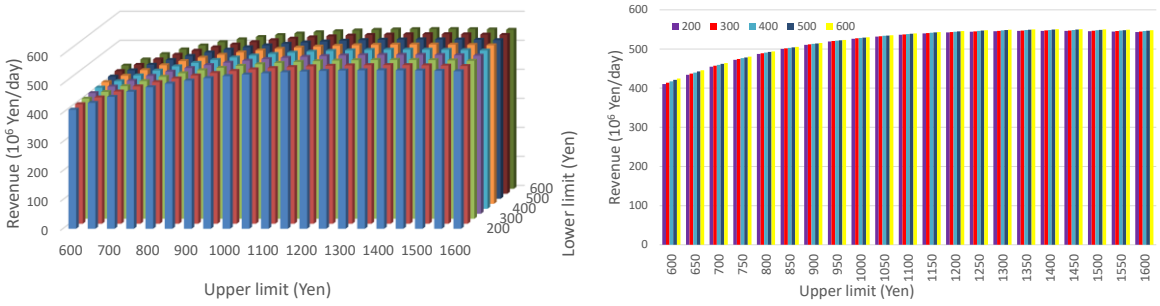


Figure 10. The change of toll revenue by traffic demand of urban area

4. MANAGEMENT OF TOLL CHARGE OF URBAN EXPRESSWAYS

The toll charging policy can be discussed with referring to long term traffic demand estimation. The essential relationship between the toll revenue and trip production in urban area can be summarized: Toll revenue would be increased through the increase of toll charge price in case of large trip production. On the other hand, the inflow traffic would be increased through the reduction of toll charge price in case of small trip production.
The update mechanism of toll charge of urban expressway corresponding to the long term traffic demand is illustrated in Figure 11.

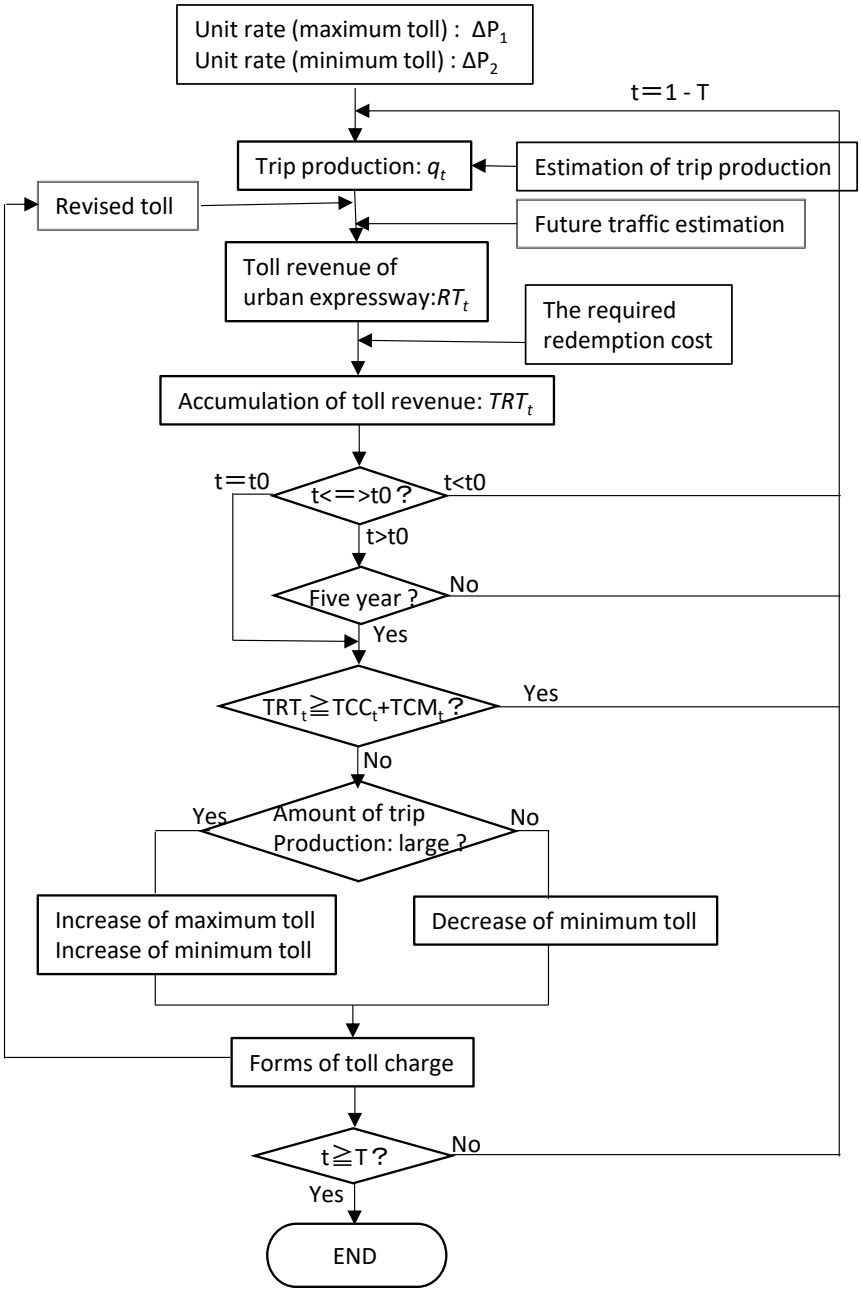


Figure 11. The update mechanism of toll charge for urban expressway

According to the toll charge function, the value of parameters such as β and γ reflect on the maximum and minimum value of toll charge respectively. Therefore, toll charge can

be updated with the change of parameters.
In the study, it is considered future toll setting by changing the set value of the lower limit and the upper limit based on current toll setting (lower limit toll, upper limit toll)=(500, 900). That is, the lower limit value is set in the range of 200 yen to 600 yen, and the upper limit value is set in the range of 800 yen to 1,600 yen. The main points of this figure are summarized.

- Consider toll level in 5 year increments
- Toll change unit is 100 yen or 200 yen.
- Revise the toll when the cumulative toll revenue is short of the assumed redemption amount.
  (1) Traffic demand is large (more than 7.5 million):
  Increase the upper limit of toll and the lower limit of toll
  (2) Traffic demand is small (less than 7.5 million)
  No upper limit change. Decrease the lower limit of toll.

The time series toll charge pattern can be illustrated in Figure 12 according to the update rules for toll charge of urban expressway. The unit price of toll is determined as 200 yen. Therefore, the maximum value of distance based toll is increased to promote the revenue every five years for fifteen years. On the other hand, the minimum value of toll is decreased to promote the expressway users after 2047.

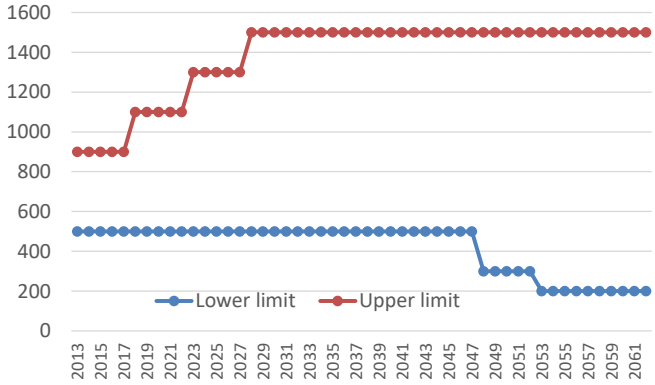


Figure 12. The time series change of toll charge for urban expressway

Corresponding to the above toll update rules, the revenue of toll will be accumulated to devote to redemption. Figure 13 shows the accumulation of toll revenue in the redemption plan. As shown in the figure, the toll revenue in the final year is -0.035 trillion yen, and the redemption is completed almost in the relevant year.

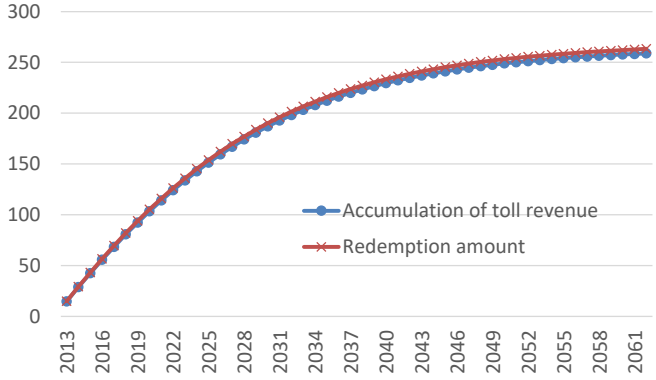


Figure 13. Accumulation of toll revenue for redemption amount

5. CONCLUDING REMARKS

Transport management policy is discussed for urban expressway referring to long term change traffic demand. The findings of the study can be summarized as follows:

1) The long term demand estimation model is created to determine the future tendency of traffic in urban area. In particular, decrease of trip production of urban area is estimated corresponding to the population as well as economic growth in super-aged society.
2) The intelligent information processing such as neural network is applied to measure the traffic condition and toll revenue of urban expressway. The method can be regarded as approximation way of traffic assignment to evaluate the essential factors of redemption plan for urban expressway
3) The time series management rules are proposed to maintain the required redemption from the revenue of toll for urban expressway. It can be essentially recommended that the price of toll would be increased in high traffic demand for urban area. On the other hand, the price of toll would be decreased in case of low traffic demand.

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